NOL HYPERSONIC TUNNEL NO. 4

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NOL HYPERSONIC TUNNEL NO. 4

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ABSTRACT: NOL's Hypersonic Tunnel No. 4 is a continuous blow-down hypersonic tunnel designed for research and development testing of models, instrumentation, and wind tunnel components. It can operate at Mach numbers from 5 to 10 with supply pressures up to 52 atmospheres and supply temperatures up to 1700°R.

This report summarizes the pertinent aerodynamic design criteria and operating experience compiled during its first eleven years of operation. Included are descriptions of the major components and their performance along with the flight simulation capability of the facility and a bibliography of previously published reports.

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The present report summarizes all available information on design and operation of the NOL Hypersonic Tunnel No. 4, which has been used during the past eleven years for development testing as well as for basic research. This report completes the documentation on the first hypersonic wind tunnel in the United States.

The authors of this report wish to acknowledge that they generated only a small part of the information contained herein and wish to give credit to the personnel from the design, research, and developmental groups within the NOL Aerodynamics Department. Unfortunately, a complete list of the people responsible for this successful project would be very difficult to compile and, therefore, names will not be mentioned. In addition to the supervisors, project leaders, and their assistants, credit has been deservedly given in all the source material to the tunnel operators and the operating and maintenance personnel who contributed to the success of the project.

R. E. ODENING
Captain, USN
Commander

K R Enkenhus

K. R. ENKENHUS
By direction

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SYMBOLS

A	area
c	velocity of sound
c_p	specific heat at constant pressure
D	diameter
g	acceleration of gravity
H	total heating rate
L	nozzle length (throat to exit)
M	Mach number
P_o	supply pressure
R	gas constant
Re	Reynolds number
T_o	supply temperature
t	time
U	velocity
W	weight of stored air
w	weight flow rate
γ	ratio of specific heats
δ	total boundary-layer thickness
δ^*	boundary-layer displacement thickness
μ	absolute viscosity
ρ	mass density

Superscripts

$*$	sonic throat conditions

Subscripts

e	effective exit conditions
max	maximum conditions
min	minimum conditions
o	supply conditions
p	pump discharge

INTRODUCTION

Hypersonic wind tunnels are highly advanced research and development facilities which are found in nearly every major aerospace research establishment. In the late 1940's there were few supersonic tunnels, and these were not, in most cases, the sophisticated instruments of today. During this period, the U. S. Naval Ordnance Laboratory's Aeroballistic Department had in operation a well-equipped supersonic wind-tunnel laboratory with an experienced staff based in part on the equipment and personnel from Peenemuende and Kochel, Germany. The familiarity of these personnel with compressible flow aerodynamics at supersonic velocities and their understanding of the coming requirements of missile technology led naturally to the proposal and design of a wind tunnel capable of exploring the range above Mach number 5. As a result, in May 1950, a 12 x 12 cm hypersonic tunnel called NOL Hypersonic Tunnel No. 4, was placed in operation, being the first practical tunnel of this kind in the United States.

From the very beginning of operation, this tunnel was used to obtain data and to establish criteria for the design and operation of future hypersonic tunnels. Little information existed, for example, on such phenomena as air liquefaction, boundary layer development in the nozzles, diffuser performance, aerodynamic heating, etc. Each of these areas and others were investigated, and through these efforts much of the design information on which many present-day tunnels are based was obtained. New instruments were developed for these investigations and conventional techniques were adapted to the new conditions. A bibliography of NOL reports pertaining to the Hypersonic Tunnel No. 4 results is given in Appendix A. Other reports of related work are included in the list of references.

As a consequence of the knowledge gained in the development and operation, the tunnel has been improved and enlarged to its present state. This report describes the current highly successful and reliable system as well as its operating conditions and limitations. The operational region of the hypersonic tunnel is shown in figure 1 together with the region covered by NOL's supersonic wind tunnels. Even though relatively high altitude conditions can be simulated in the hypersonic wind tunnel, it still operates completely in the continuum flow regime. The trajectories of glide vehicles and ballistic missiles are shown to illustrate the tunnel's suitability for the study of parameters and phenomena of interest to the designer of such vehicles. The upper boundary of the regime corresponds to operation with a supply air pressure of 5 atmospheres, and the lower boundary to 52 atmospheres.

For operation at any of the conditions within the indicated regime, it is necessary to preheat the supply gas to avoid air liquefaction in the test section. Early experiments (ref. (1)) had shown that liquefaction begins at the equilibrium condensation point. The supply temperatures needed to prevent equilibrium condensation in the test section are shown in figure 2 for various Mach numbers.

MAJOR COMPONENTS OF THE HYPERSONIC TUNNEL

A functional schematic layout of Hypersonic Tunnel No. 4 and its auxiliary equipment is shown in figure 3. As now constituted, it is a Mach 5-10 tunnel which is blow-down operated from a maximum stagnation pressure of 52 atmospheres to a low pressure reservoir of 4 mm Hg minimum. The size, as defined by the maximum nozzle exit area, is three quarters of a square foot. An artist's conception of the existing tunnel is shown in figure 4, and a photograph of the working section within view of the operator can be seen in figure 5. Figure 6 is a drawing showing the general arrangement of the principal components and their significant dimensions.

The tunnel operates from a 3000 and 5000 psi supply of stored air which has been filtered and dried. Pressure-regulating valves control the pressure of the air supplied to the tunnel in the range from 5 to 52 atmospheres. A gas-fired indirect heat exchanger and an 80 KW electric resistance heater control the supply temperature in the range from room temperature to 1700°R.

The tunnel is started by opening a quick-acting slide valve immediately upstream of the nozzle inlet section. The resulting flow of air is expanded in two-dimensional fixed block or axially symmetric nozzles to the desired Mach number. Downstream of the test section the air is decelerated in a convergent-divergent, adjustable area diffuser. All tunnel components exposed to the air flow are water cooled to minimize thermal stresses and maintain constant tunnel geometries. Low diffuser exit pressures are maintained by either of two available low pressure pumping systems - a rotary vane pumping plant or a centrifugal compressor plant. The following sections describe in greater detail the components and their mode of operation.

Air Supply

The compressed air storage system consists of 1420 cubic feet of air contained in 3000 psi gas bottles and 900 cubic feet of air contained in 5000 psi gas bottles. The 3000 psi and 5000 psi bottles have an average unit capacity of 22 cubic feet and 28 cubic feet, respectively. Altogether they have a gross

capacity of about 42,000 pounds of air. Figure 7 shows the weight of air stored in the combined bottle field as a function of the storage pressure.

Air is supplied to the storage system by twelve four-stage, reciprocating compressors having a combined delivery rate of 2.4 pounds per second at their maximum design output pressure of 3000 psi. It is further compressed to 5000 psi by a single stage, reciprocating booster unit having a capacity which nearly matches the 3000 psi units. The 3000 psi machines are the horizontal type employing inter-stage and after-stage cooling. The booster unit is vertically configured and employs after-cooling also.

Dehumidification of the air is accomplished partially in the compressor after-coolers but primarily in dryers containing an alumina-type desiccant. These dryers are capable of maintaining a dew point of -72°F. The reactivating cycle of the dryers consists of passing electrically heated air at 350°F through the saturated desiccant bed followed by a cooling cycle utilizing cool dry air.

Air Storage Recovery

The time required to recover or pump up the air storage field can be computed from the combined compressor recovery rate. Figure 8 is a plot of the time required to add a given number of pounds of air to the storage field. If the field is completely empty, 4.75 hours are required to fill it to 42,000 pounds. Since the storage field pressure is monitored on the tunnel control panel, figures 7 and 8 can be used to estimate recovery times between any given pressure conditions in the field.

Pressure Regulation

The supply air pressure is regulated by either one of two pneumatically controlled, contoured plug valves. The valves have body sizes of 4 inches and 2 inches, trimmed down to 2 inches and 0.75 inch, respectively. They are connected in parallel and sequentially operated to handle the mass flow and pressure requirements. Valve selection is such that weight flows between approximately 0.4 lb/sec to 30 lbs/sec can be easily controlled. Automatic controllers maintain the tunnel stagnation pressure at any desired control point within the range from 5 to 52 atmospheres within $\pm$ 1.5 psi. The control pressure is sensed at the air supply section immediately in front of the nozzle inlet section. The controllers, together with the various gauges and recorders which provide coarse and

fine indications as well as records of the supply pressure and air storage pressure, are mounted in two instrument racks adjoining the operator's console (see fig. 9).

Primary Air Heater

The indirect gas-fired heater is installed outdoors (fig. 10) and vertically above the wind tunnel. Including the accessory equipment, such as the combustion blower, control valves, and control devices, and instruments which must be locally mounted, the installation is unsheltered. The exterior casing is 12 feet in height and 6 feet in diameter. The heater itself weighs less than 5 tons.

Designed for a maximum pressure of 100 atmospheres, the heater has wide load handling capability. At the maximum heating rate of 1400 Btu/sec, the unit will process air weight flows between 4 and 28 lbs/sec, the corresponding air delivery temperatures being 1200°F and 200°F, respectively. These two performance extremes correspond very nearly to Mach 10 and Mach 5 at stagnation pressures of 100 atmospheres and 25 atmospheres, respectively. At lower output the heater will process air weight flows extending down to about 0.4 lb/sec and still produce delivery temperatures between 750°F and 1200°F. See figure 11 for the complete performance envelope. Pressure drop through the heater is limited to a maximum of 10 percent of the inlet pressure. A 10 percent pressure drop is considered to be tolerable for the vast majority of operating situations and at the same time is a sufficiently generous allowance to enable a highly compact and efficient heat exchanger design to be achieved. Throughout most of the operating region the pressure loss is considerably less than 10 percent.

Temperature fluctuation in the heater discharge is designed not to exceed $\pm$ 1 percent over the entire load range. At moderate weight flows and pressures the temperature stabilization is considerably better than $\pm$ 1 percent. Variations of not more than $\pm$ 4°F at temperatures ranging up to 1200°F have been consistently observed.

Supply temperature control is performed manually or automatically from the control center using proportioning controller-recorders equipped with automatic reset and rate action. The controller output is applied to pneumatically activated valves which modulate the burner combustion air, fuel gas, and dilution air. Temperature sensing for control purposes is made in the 8-inch diameter heater discharge pipe. A drop of 50 to 100 degrees Fahrenheit is commonly experienced between the control point and the nozzle inlet depending on the load and temperature level. As this drop is invariant after reaching the operating

state, its magnitude is only important insofar as it diminishes the maximum achievable stagnation temperature. The relatively large temperature drop is the result of convective losses occurring along the length of the large expansion loop in the hot piping, a construction that was necessary to limit the thermal stresses to an acceptable level.

The heat exchanger itself is basically a two-pass, counter-flow unit. A refractory-lined baffle separates the passes. Process air enters a toroidal manifold at the top of the heater, flows downward through the outer pass, and then upwards through the inner pass where it is convectively and radiantly heated by the incoming combustion gases. The heat exchanger is designed on the basis of a stress to rupture in 10,000 hours at maximum conditions. Response rates of 60°F per minute are typical for initial warm-up, whereas rates several times greater are attainable for subsequent load excursions of moderate span. The response characteristics of the entire installation have been improved by lining the interior of the pressure piping connecting the heater to the tunnel with thin-walled stainless steel pipe covered with insulating blanket.

A top mounted, forced draft, downward firing burner consuming propane gas provides the hot combustion gases for heat transfer. Rated thermal efficiency of the burner-heat exchanger combination is 60 percent at 4.5 pounds per second of process air and 1200°F outlet temperature. At higher weight flows the efficiency improves, approaching 70 percent as a maximum value.

Electric Heater

An electric resistance heater, contained in a pressure vessel suspended from roof framing above the tunnel room, supplements the output of the primary heater. Approximately 80 Btu/sec can be transferred to the air stream at optimum conditions. The resistance elements are nichrome wire coils wound on ceramic cores placed in cross flow. The maximum electric power input is 80 KW, derived from 400 volt, a.c., source. A part of the original installation, this unit has a safe working pressure rating at room temperature slightly in excess of 1000 psia. At elevated temperatures, it is reduced to 930 psia at 750°F and 750 psia at 900°F. A loose fill, refractory base, fibrous insulation possessing a continuous service temperature above 1200°F, maintains the temperature of the pressure vessel below 400°F at the maximum condition. For practical purposes, therefore, the heater, together with the tunnel in its present form, is pressure limited at 1000 psia. Temperature control is more rudimentary than in the case of a number of equal resistance banks, an integral number of which are energized to meet the

approximate load requirements. A separate bank, equipped for simple on-off regulation, then provides the fine control.

By-Pass System

Inserted between the electric heater and the slide valve is a by-pass line containing a manually operated throttling valve. When the valve is open high pressure air can be exhausted directly to the atmosphere prior to establishing flow in the tunnel, thus permitting preheating of the heater and other upstream equipment. Also, when the tunnel is stopped for short durations, the heater can be maintained at relatively high temperatures. In both instances, diversion of the hot air through the by-pass diminishes substantially the time to establish or re-establish operating conditions while sustaining only a comparatively small loss of stored air. A further function of the by-pass system is to provide a forced air flow over the heat exchange surfaces and other high temperature parts during the immediate post shut-down period. This prevents the overheating of critical components in the heater that would occur if the air flow were suddenly stopped. For preheating, by-pass pressures in the range of 50-150 psi and heating outlet temperatures in the region around 1000°F are highly effective.

Tunnel Operating Valve

The final event in the tunnel flow starting sequence is the opening of the tunnel operating valve located between the heaters and the nozzle section (see fig. 5). The valve is a quick-acting device, having a pneumatically driven horizontal slide with a 4-inch x 6.25-inch rectangular opening. Sealing is effected by metal-to-metal contact between the stainless steel slide and the cast, low-alloy carbon steel body. The latter is water cooled. Valve stem cooling is achieved through extended surface bonnet construction. An air cylinder type actuator, using a low pressure (75-95 psia) supply, strokes the valve in approximately 0.5 seconds. The valve assembly possesses a temperature-pressure rating nearly identical to the electric topping heater, and, therefore, imposes the same operational limitation.

Valve operation is controlled at the main control console. Electrical permissive circuits functioning to prevent energizing of the valve actuator accidentally or under improper operating conditions must be satisfied before the valve can be operated. In addition, a manually engaged mechanical lock on the valve stem ensures personnel safety while test preparations are made inside the tunnel.

Settling Chamber

Situated between the tunnel operating valve and the nozzle is a chamber which functions both as an air stagnating and filtering unit. Figure 12 shows side and bottom views of this section. It is also in this unit that the stagnation pressure and temperature are measured.

The upper portion of this section contains the filtering unit which consists of a box-shaped particle-trap surmounted by a solid pyramidal fairing to redirect and distribute the oncoming flow and to absorb the flow impact. This construction can be seen in figure 12. A 325 mesh, 0.0014-inch stainless steel wire cloth reinforced by 6 mesh, 0.025-inch stainless steel wire cloth stops particles larger than about 30 microns. Filtering action is further promoted by the relatively large frontal area presented to the flow and the oblique impingement induced by the severe change in the flow velocity vector. A rectangular access port is provided to allow rapid removal of the filter for servicing and cleaning purposes. A pressure monitoring system is used to detect the build-up of dirt on the filter element. Cleaning and inspection of the filter take place whenever the pressure monitor indicates a pressure drop of 5 psi.

The filter is followed by a large duct sized to reduce the flow velocity to less than a Mach number of 0.015. Turbulence is reduced to a practical minimum by a cascade of four screens ranging from 20 mesh to 100 mesh in the direction of flow. The effectiveness of these and other measures designed to produce high quality flow is treated in the section on performance.

The filter and turbulence reducing elements are contained within a stainless steel duct which, in turn, is housed within a forged stainless steel pressure chamber, jacketed with rigid sheet insulation. The entire assembly has a working rating of 100 atmospheres at 1300°F. Uncooled metal gaskets are used in the side access port whereas water-cooled silicone rubber gaskets seal the end flanges.

Nozzles

The aerodynamic design procedure for the two-dimensional flow (block type) nozzles is described in reference (2). Reference (3) treats the aerodynamic design of the axially symmetric nozzles and more fully describes their mechanical design and construction. Nozzles used in this tunnel are of the fixed contour type; both two-dimensional, rigid block, and axially symmetric nozzles are available. The rigid block nozzles have given satisfactory service in the medium Mach number range; axially symmetric nozzles have found almost exclusive

service at Mach 8 and above. The problems associated with high and low pressure sealing, elevated temperatures, dimensional instability, surface precision, and contour tolerances are more difficult at the higher Mach numbers, making the axially symmetric nozzle an attractive design for these conditions. Table 1 lists the nozzles which are available for this tunnel.

The nozzles are suspended from the air stagnation chamber, and in the case of the block-type nozzle they serve as the structural link between that section and the test section. A separate tunnel suspension is used with the axially symmetric nozzles in order to minimize loading of the comparatively fragile contoured shell.

Each rigid block nozzle is composed of identically formed and contoured blocks mounted between plane, divergent sidewalls to form Laval-type nozzles which will generate a two-dimensional uniform parallel flow. Divergence of the sidewalls compensates for the sidewall boundary layer growth.

The nozzle blocks are stainless steel weldments, precision machined and polished to produce the desired aerodynamic profile. To improve the dimensional stability of the Mach number 8 two-dimensional nozzle in the sonic throat region, a high purity nickel throat insert, in which cooling channels were machined, was joined to the principal block by welding. Figure 13 is a cutaway view of the throat insert and the adjoining portions of the main block for this nozzle. Since cooling requirements in the expansion region of the nozzle are several orders of magnitude lower than at the throat, a more conventional design has been applied to the main block. A series of holes drilled crosswise to the flow and parallel to the profile, suitably manifolded, serve as the cooling passages.

The Mach number 6.7 two-dimensional nozzle, operating at a lower temperature, has no throat insert. The entire cooling arrangement is similar to the expansion section of the Mach number 8 two-dimensional nozzle. The sidewalls are stainless steel weldments into which cooling passages have been milled and a welded stainless steel cladding overlaid to form the flow side surface. Coolant velocities and total pressures are in the same range as those for the coolant circulated through the main block. An assembled block type nozzle, set in place in the tunnel, is shown in figure 5.

The axially symmetric nozzles were formed by electrolytically depositing high purity nickel on a precisely machined mandrel. With this method, wall contour accuracies of $\pm$ .0002-inch and surface finishes as fine as 4-8 micro-inches are commonly

obtainable. The electrolytic depositing process affords excellent control over the wall convective cooling system geometry. By interrupting the process at an appropriate time, cooling channels can be formed by conventional machining operations. The construction of the Mach 8 axially symmetric nozzle is schematically represented in figure 14. Shown also are the nozzle and mandrel. The cooling channel depicted in figure 14 is a simple annulus having the inlet and outlet 180° apart.

Test Section

The main design criteria were spaciousness, freedom from internal obstruction insofar as practicable, generous provision of precisely aligned mounting surfaces, and a high degree of accessibility. These criteria were in consonance with the aerodynamic requirements to accommodate a large variety of models and test instrumentation.

The test section (fig. 15) is a ruggedly constructed reinforced box weldment. Two of the opposing sidewalls are fitted with large rectangular hinged access doors, which can be quickly unlatched to permit ready and convenient access to the interior. Circular ports are provided in each door to receive a variety of 11-inch diameter, interchangeable utility panels. The other two sides of the chamber are closed by light weight, bolted cover plates which facilitate the installation and servicing of the bulky apparatus and instrumentation, such as the model attitude and support mechanism.

Also interchangeable with the utility panels are the schlieren optical windows. The windows are 1-inch nominal thickness prime schlieren quality, fuzed silica, yielding an 11-inch diameter field of view. A cushioned mounting, illustrated in figure 16, provides the necessary restraint to obtain a close fitting, flush, aerodynamically acceptable internal surface joint without inducing edge moments and stresses of sufficient magnitude to cause spalling.

The chamber interior can be modified for a completely open, half-open, or closed-jet configuration. The last configuration is difficult to produce from the practical standpoint because of the many irregular penetrations normally required for instrumentation. Coolant passages in the test section walls are formed by welding stainless steel sheets over pre-machined channels in the base structure. In addition to reducing the thermal stress and distortion in the structure, the cooling system affords protection of the elastomeric seals. Seal cooling is far more critical than general structure cooling and for this reason separate cooling circuits are employed for each seal, the passages being formed as close to the seal itself as fabrication methods permit.

Diffuser

The type of diffuser developed for this tunnel is a two-dimensional flow duct incorporating hinged plates which can be positioned to produce a single throated, converging-diverging duct. The diffuser can assume a large range of area ratios. Openings at the inlet, throat, and exit can be adjusted from 10 inches to 14 inches, 0 inch to 11 inches, and 1 inch to 12 inches, respectively. Total diffuser length is 7 feet, the supersonic-to-subsonic diffuser duct length ratio being about 1 to 2.5.

In the Hypersonic Tunnel No. 4 installation, the greater portion of the diffuser is situated below the main floor level as is illustrated in figure 3. A full length external view of the unit is shown in figure 17. The electric motor powered drives for the adjusting screw jacks at the throat and discharge are prominently projecting from the sides. In figure 18 a sidewall has been removed to reveal the variable area flow duct.

The diffuser throat is constrained to open and close in a fixed horizontal plane whereas the inlet and discharge openings shift as necessary to accommodate the resulting axial movement. The motorized drives can produce changes in the diffuser configuration at the total rate of 10 inches per minute at the throat and 8 inches per minute at the discharge. Manual adjustment is provided at the inlet inasmuch as this station does not require frequent nor rapid change of the opening. In contrast to the other stations where the duct dimensions may be altered during tunnel operation, the inlet opening is set prior to starting the flow and invariably remains fixed during a test. Adjusting the diffuser area is a function which can be performed simultaneously at any or all of the three pairs of position-setting jacks under static or dynamic air loading. The plates and adjusting mechanisms are both mechanically and electrically protected from over-travel at either extreme. The inlet and the throat joints are matched and contoured to present faired surfaces to the flow through the normal range of motion. A solid teflon insert installed in the throat "knuckle" joint prevents back flow through the joint. A pair of flexible seals block the back-streaming of air from the diffuser exhaust through the void between the movable plates and the external casing. Undesirable leaks along the length of the ducts are prevented by solid round cord packings set into the edges of the movable plates.

Two service panels, approximately 2 feet square, are installed in each fixed sidewall of the diffuser structural casing. The one installed in the general area of the inlet and throat stations is to facilitate the in-place maintenance and repair of the kinematic and sealing systems which otherwise would require

the removal and complete dismantling of the entire unit. Each of the panels contains a 10-inch diameter utility port, through which special instrumentation, probes, and models can be inserted. The other panel is located in the extreme downstream portion of the sidewall. The sidewalls shown in figure 17 are an earlier design which did not specify the large service panels. This latter feature was added when new walls were constructed. In the new walls, coolant passage construction is based on a design approach that is different from the criteria adopted for equipment of earlier design. In the more recent design all welding, for structural as well as for coolant purposes, is performed on the exterior of the weldment so as to prevent any leaks along the flow side surface.

Installed in one of the 10-inch panels at the diffuser entrance is an over-pressure relief valve set to open automatically at 1 psi above ambient pressure. Its function is to protect personnel and the tunnel equipment against high pressure which might occur under emergency vacuum pump shutdown conditions. Under most emergency shutdown conditions, however, there is sufficient time to secure the high pressure system because of the relatively large volume in the downstream piping. Structurally the diffuser will withstand much higher pressures but there are a number of somewhat delicate items, notably the schlieren windows, certain internal seals, and instrumentation, which would be irreparably damaged by over-pressure.

Gate Valve

The tunnel may be isolated from the main vacuum manifold by means of a 16-inch diameter motor-driven wedge-type gate valve. This valve is electrically interlocked with the upstream slide valve so that it cannot be closed while the tunnel is operating. By closing first the slide valve and then the isolating gate valve, the tunnel working section can be isolated from both the high pressure and low pressure system. The gate valve design and construction materials are standard for low pressure, moderate temperature, gas service. Water cooling has not been found necessary.

Aftercooler

The aftercooler is a shell and tube cross-flow heat exchanger. The two extreme design conditions for this unit are (1) inlet air temperature of 1250°F, inlet pressure of 0.89 psia, and weight flow of 2.4 lbs/sec, and (2) 190°F inlet temperature, 7.73 psia inlet pressure at weight flow of 28 lbs/sec. In all cases the exit temperature is 150°F, and the pressure drop through the coils does not exceed 10 percent of the inlet pressure.

Maximum coolant requirements are 300 gpm of water at 85°. maximum and 70 psia minimum through the tubes plus a nominal flow in the shell water jacket.

Vacuum Pumps

The primary plant which provides the pumping capacity for Hypersonic Tunnel No. 4 as well as the other continuous tunnels of the Naval Ordnance Laboratory testing complex consists of four multi-stage centrifugal compressors. Each of the four compressors has a separate electric motor drive. The total available power is nearly 9,000 KW, but the normal power consumption for this tunnel is only 2,200 KW. Figure 19 shows the measured overall performance of all four compressors operating in series. This is the principal operating configuration. Reference (4) fully describes the plant and discusses its operation and performance.

PERFORMANCE

Discharge Rates

The discharge rate of weight flow varies considerably in the range of conditions of interest for Hypersonic Tunnel No. 4. One of the important factors is the exit area of the nozzles available. Although the tunnel is considered to have a nominal exit area of 10 x 10 inches, the available nozzles have the physical dimensions given in Table 1. In order to compute approximately the discharge rate, the effective area of the nozzle exit must be calculated, i.e., the boundary layer displacement thickness must be taken into account. The latter can be obtained from measured values of the total boundary layer thickness and the tabulated data of δ^*/δ (ref. (6)).

Discharge rates can be calculated from

$$w = g\rho^* U^* A^* = \rho_o \, c_o \, \frac{\rho^*}{\rho_o} \sqrt{\frac{T^*}{T_o}} \, \frac{A^*}{A_e} \, A_e \qquad (1)$$

The term $\frac{\rho^*}{\rho_o}\sqrt{\frac{T^*}{T_o}}$ is a constant and is equal to 0.579.

With P_o in atmospheres, T_o in degrees Rankine, and w in lb/sec. equation (1) can be written as

$$w = 1125 \, \frac{A^*}{A_e} \, \frac{P_o \, A_e}{\sqrt{T_o}} \qquad (2)$$

Figure 20 shows the resulting mass flow computed using minimum temperatures to avoid equilibrium condensation. The limits of operation are indicated on the figure. The lower limits and the upper limit at M = 6.7 are associated with heater control limitations.

Figure 21 shows the entire envelope of operating conditions for three of the nozzles. The reason for each operating limitation is indicated on the figure.

Calibration Data

Figures 22 through 24 are detailed calibration curves for three of the nozzles. For each nozzle, the M = 6.7 two-dimensional and the M = 8 and M = 10 axisymmetrical nozzles, two curves are presented showing the axial Pitot pressure distribution and the Pitot pressure in a plane normal to the flow direction near the nozzle exit. The supply conditions indicated on these figures represent the design conditions for these nozzles.

The curves themselves best illustrate the high quality of these nozzles. Many similar curves are available for off-design conditions. However, it is possible to calculate the change in Mach number near the nozzle exit due to off-design operation by the following approximate method. The local Mach number is obtained from standard isentropic flow tables corresponding to an effective area ratio

$$\frac{A_e}{A^*} = \frac{A_e}{A^*}(M_e) \tag{3}$$

The throat area, A^*, is assumed to remain equal to the geometric area (see Table 1 for nozzle dimensions) independent of supply conditions. The effective exit area (A_e) is the geometric area at a given station near the exit less the area between the physical wall and the average displacement thickness (δ^*). The average displacement thickness can be calculated from the following empirical formula, which is suitable for the available nozzles (see figure 25)

$$\frac{\delta^*}{L} = .33\ Re_L^{-1/5} \tag{4}$$

Blockage

Tests have been conducted with five representative model configurations to determine maximum model dimensions permissible for three of the nozzles. In these tests each model was mounted near the nozzle exit and the tunnel diffuser was in the fully-open position. The test was started at the normal condition of 9 to 10 atmospheres supply pressure and 4 mm Hg end pressure. The establishment of hypersonic flow was determined from Pitot pressure measurements.

There are two techniques for starting the tunnel: "fast starting" and "slow starting". Fast starting is the normal method of establishing flow by means of the quick-acting slide valve. Slow starting describes the situation where flow through the nozzle is permitted but with insufficient pressure ratio. The supply and end pressures are then manually regulated so as to increase the pressure ratio until proper flow is achieved.

The results describing the maximum model size permissible for starting flow by the fast starting method are shown in Table 2. It is evident from this table that blunt bodies have a smaller maximum starting diameter than more streamlined shapes. In some cases, if the body is initially put at an angle of attack, the tunnel may be started with a blunt body whose diameter exceeds the value given in Table 2.

The basic limitation on the angle of attack range possible with a given model is that at some angle the tunnel boundary layer will separate. The specific angle will, in general, depend on model configuration and thickness of the wall boundary layer. With moderately blunt models, tests have been run at angles of attack up to 13°. With smaller models, damping tests involving complete rotation of the model have been successfully performed.

Diffuser Recovery

The efficiency of the diffuser has been investigated thoroughly for the early configurations of Hypersonic Tunnel No. 4. These results were reported in NAVORD Report 2376. The earlier results indicate a maximum operating end-pressure, without causing flow breakdown, of about twice the test section Pitot pressure. These studies were made with a two-dimensional wedge nozzle exhausting directly into the diffuser inlet (i.e., a closed jet). Since its modification, operation of the tunnel can optionally be in an open-jet, partially closed-jet, and completely closed jet configuration with correspondingly varying diffuser efficiency. Partially closed or completely closed-jet operation is most conveniently arranged with the two-dimensional nozzles. Jet plates which extend the nozzle contour can be installed whenever

instrumentation permits it and a high recovery is needed. With partial closing, an operating end pressure of 1.1 times the Pitot pressure is maintained. With the axially symmetric Mach number 8 and 10 nozzles, and the flow exhausting into the two-dimensional test section and diffuser as a more or less open jet, the permissible end pressure ratios are 0.55 and 0.72, respectively. Since the present compressor plant has sufficient low pressure pumping capacity the tunnel is very often operated with a straight duct diffuser without concern for the end pressure value. Only for the most severe blockage conditions is it necessary to adjust the diffuser for optimum pressure recovery.

Simulation Capability of Hypersonic Tunnel No. 4

The Reynolds and Mach number capability of Hypersonic Tunnel No. 4 are shown in figure 26. This figure was obtained by computing the maximum and minimum Reynolds number which may be obtained in each of the three nozzles - the Mach number 6.7, 8 and 10 nozzles.

INSTRUMENTATION

Four types of tests are carried out in Hypersonic Tunnel No. 4. They are:

a. Model pressure, temperature, and heat-transfer distributions.

b. Force and moments.

c. Probing flow fields.

d. Optical.

In the following sections the major instrumentation that is available for performing the above tests is described along with the data recording facilities at NOL.

Model Pressure, Temperature, and Heat-Transfer Distributions

An important part of the testing of scale models at high Mach numbers is concerned with measuring the pressure and temperature distribution on the surfaces of models and heat-transfer distributions. Heat-transfer data may be obtained with transient techniques or because of the long blowing time possible for most Hypersonic Tunnel No. 4 conditions, steady-state methods may be used.

A water-cooled sector mechanism is available for mounting models in the tunnel with an angle of attack range of $\pm$ 20°.

Detachable sections are available to give other ranges of angle of attack with respect to the flow. The center of rotation is on the tunnel centerline at the nozzle exit. The distance from the angular position is detected by a syncro-system, the output of which is displayed continuously and can be automatically recorded.

Force and Moments

Normal force and pitching moment measurements also represent a considerable part of the development testing performed in Hypersonic Tunnel No. 4. This type of testing is performed using water-cooled strain-gage balances developed for use in the hypersonic tunnel. Reference (8) describes their characteristics.

Probing of Flow Field

Flow research data in the hypersonic tunnel are gathered largely with probes, i.e., small instruments designed to detect local pressure (static or Pitot), total temperature (ref. (9)), equilibrium temperature (ref. (10)), mass flow (ref. (11)) or gas concentration. These probes are used to investigate the principal flow fields such as the nozzle and diffuser flow, or instruments can be constructed which are suitable for surveying the boundary layer on the tunnel walls or on specially constructed models.

Mechanical drive systems have been developed to support and position the probes. These include a two-directional traverse mechanism for nozzle-diffuser calibration as well as automatic and hand-operated micrometer traverse mechanisms for more accurate cross-flow measurements such as in the boundary layer. The two-directional traverse mechanism can be installed in the access ports of the test section and diffuser. It has a maximum travel of 26 inches in the flow direction and 6 inches perpendicular to the flow.

The manually operated micro-traverse is a water-cooled micrometer with a one-directional travel of 2.6 inches. A vernier readout allows positioning accuracy of better than $\pm$ .001 inch. The automatic traversing mechanism is a motor driven micrometer permitting a one-directional movement of 3 inches with an accuracy of $\pm$ .001 inch. A manually operated lead screw can be used to move the automatically driven arm unit perpendicular to the direction of the automatic drive. A maximum travel of 10 inches is possible in this direction.

Data Handling

Two automatic data recording systems are currently in use at NOL. The older system known as "PADRE" (Portable Automatic

Data Recording Equipment, (ref. (12)) is suitable for recording any quantity represented by an a.c. or d.c. voltage. Seven channels with servo-systems and digital convectors are provided. The output is punched onto IBM cards. The new system is the Epsco Data Processing System which records up to 80 voltage inputs per second on magnetic tape. Both systems can be used as inputs for NOL's IBM 7090 computer for programmed data reduction.

Optical Instrumentation

A two-mirror, color, or black-and-white schlieren system is available for general studies of the flow field. To eliminate the disturbing effects of room air convection, the system is completely enclosed and can be tightly sealed to the tunnel windows. Light sources of various intensities including an 8 KV spark source of 0.6 microsecond duration are available either for single exposure or normal speed motion pictures.

SUMMARY AND CONCLUDING REMARKS

NOL's Hypersonic Tunnel No. 4 is designed for aerodynamic research and development testing. It operates in the Mach number range from 5 to 10 with supply pressures up to 52 atmospheres and at supply temperatures up to 1700°R.

Major components of the tunnel system that are described include the air storage, pressure and temperature regulators, nozzles, test section, diffuser, and the vacuum pumping system. Four contoured nozzles are currently available for this tunnel. Two are Mach numbers 6.7 and 8 two-dimensional nozzles, and two are Mach numbers 8 and 10 axisymmetric nozzles.

Performance of the main components is described from the point of view of the user of the tunnel. The limiting factors on the flow conditions obtainable in the test section (e.g., air liquefaction, mass flow, running time, and blockage, as well as the uniformity of the usable flow) are discussed.

Perhaps the outstanding features of this tunnel have been the complete absence of serious mechanical difficulties, high quality nozzles and instrumentation, large air storage capacity, low pressure pumping capability and a highly reliable and easily controlled heat source. It is notable that its modification was accomplished in approximately six months with testing beginning immediately.

Because of this, the Hypersonic Tunnel No. 4 has been used extensively for detailed studies of turbulent boundary layers, with emphasis on the effects of heat and mass transfer on

boundary layer characteristics, the investigation of heat transfer to various blunt-nosed bodies, and related studies requiring a close control of operating conditions for extended periods.

It is also significant that this tunnel which pioneered the field in hypersonic flow is again being modified to extend its range. A graphite resistance heater has recently been added to increase its range to Mach 17.5. Because of oxidation problems at the required temperatures (4500°R), nitrogen is being used as the test gas.

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APPENDIX A

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(10) Liccini, L. L., "Hypersonic Tunnel No. 4 Results IX: The Development of a Water-Cooled Strain-Gage Balance (Including Sting Effects) and Its Application to a Study of Normal Force and Pitching Moments of a Cone and Cone-Cylinder at Mach Numbers 5 to 8," NAVORD Report 4334, Aug 1956

Table 1

AVAILABLE NOZZLES

Mach No.	Type	Throat in.	Dimensions Exit in.	Throat to Exit Length in.	Material
6.7 (1)	2-D	8.17 x .080	10 x 9.3	65	347 Stainless Steel
8 (1)	2-D	8.17 x .043	10 x 10	65	Nickel-Steel (nickel throat block)
8	A-S	.510 dia.	8.175 dia.	45	Electroformed Nickel
10	A-S	.434 dia.	12.340 dia.	60	Electroformed Nickel

(1) These nozzles have four access ports suitable for mounting 10-inch diameter windows.

Table 2

MAXIMUM MODEL DIAMETERS TO PREVENT FLOW BLOCKAGE

(Fast Starting Method)

Nozzle Mach Number	6.7		8		10	
Nozzle Exit Dimensions	10 x 9.3		8.175 dia.		12.340 dia.	
	D_{max}	A_{max}/A	D_{max}	A_{max}/A	D_{max}	A_{max}/A
Sphere	3.25	.089	3.50	.175	2.00(1)	.0262
Disk	3.00	.076	2.00	.057	2.00(1)	.0262
10" Rod	1.75	.188	1.38	.208	.500(1)	.0418
10° Cone (total angle)	4.5(2)	.171	4.5(2)	.290	4.5(2)	.1330
20° Cone (total angle)	4.5(2)	.171	4.5(2)	.290	4.5(2)	.1330

D_{max} - model diameter, inches

A_{max} - projected model blockage area

A - physical opening of nozzle at the exit

(1) - both fast and slow starting

(2) - largest model tested

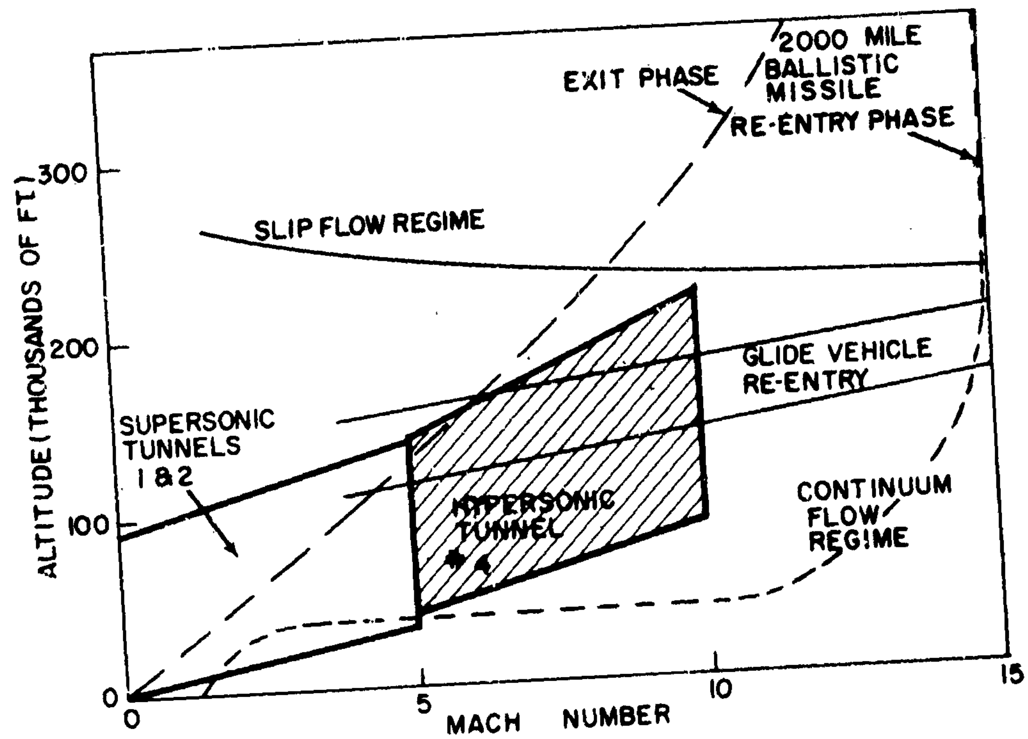


FIG. 1 HYPERSONIC TUNNEL NO. 4 OPERATING REGION

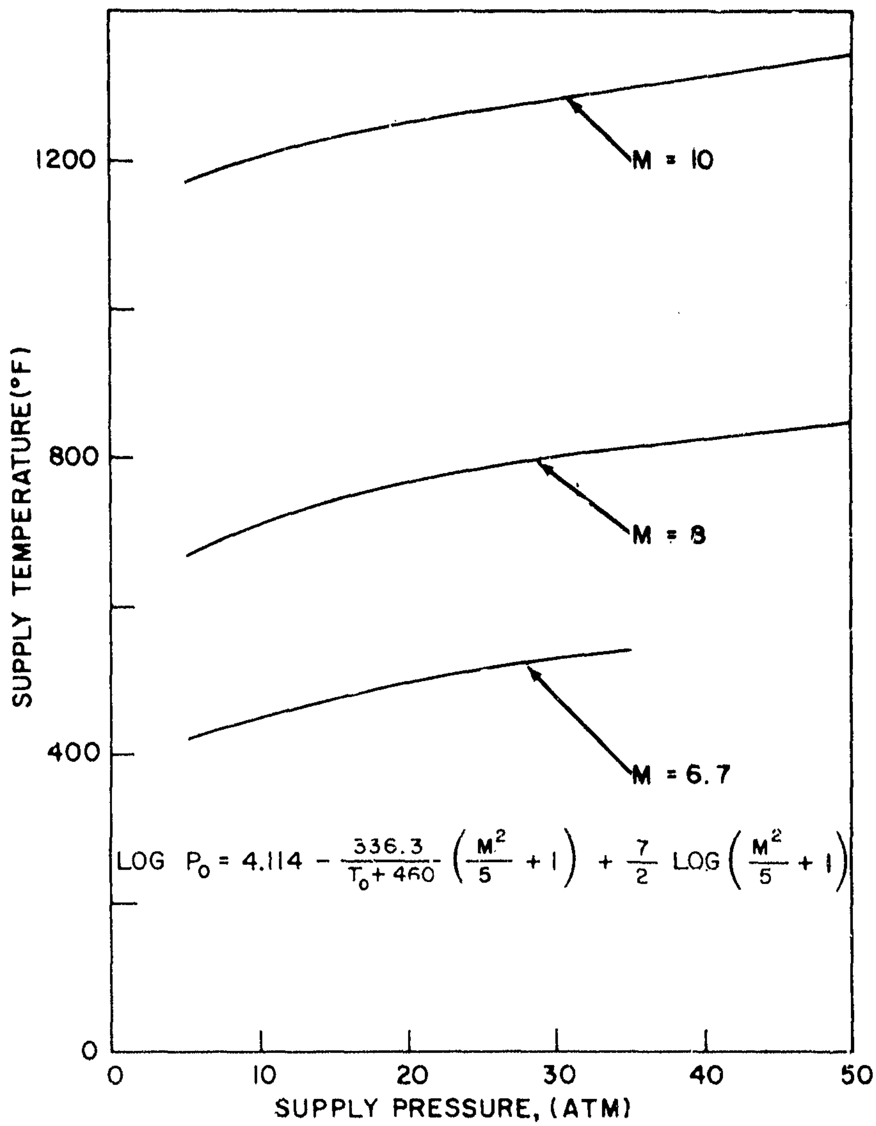


FIG. 2 VARIATION OF SUPPLY TEMPERATURE WITH SUPPLY PRESSURE (EQUILIBRIUM CONDENSATION)

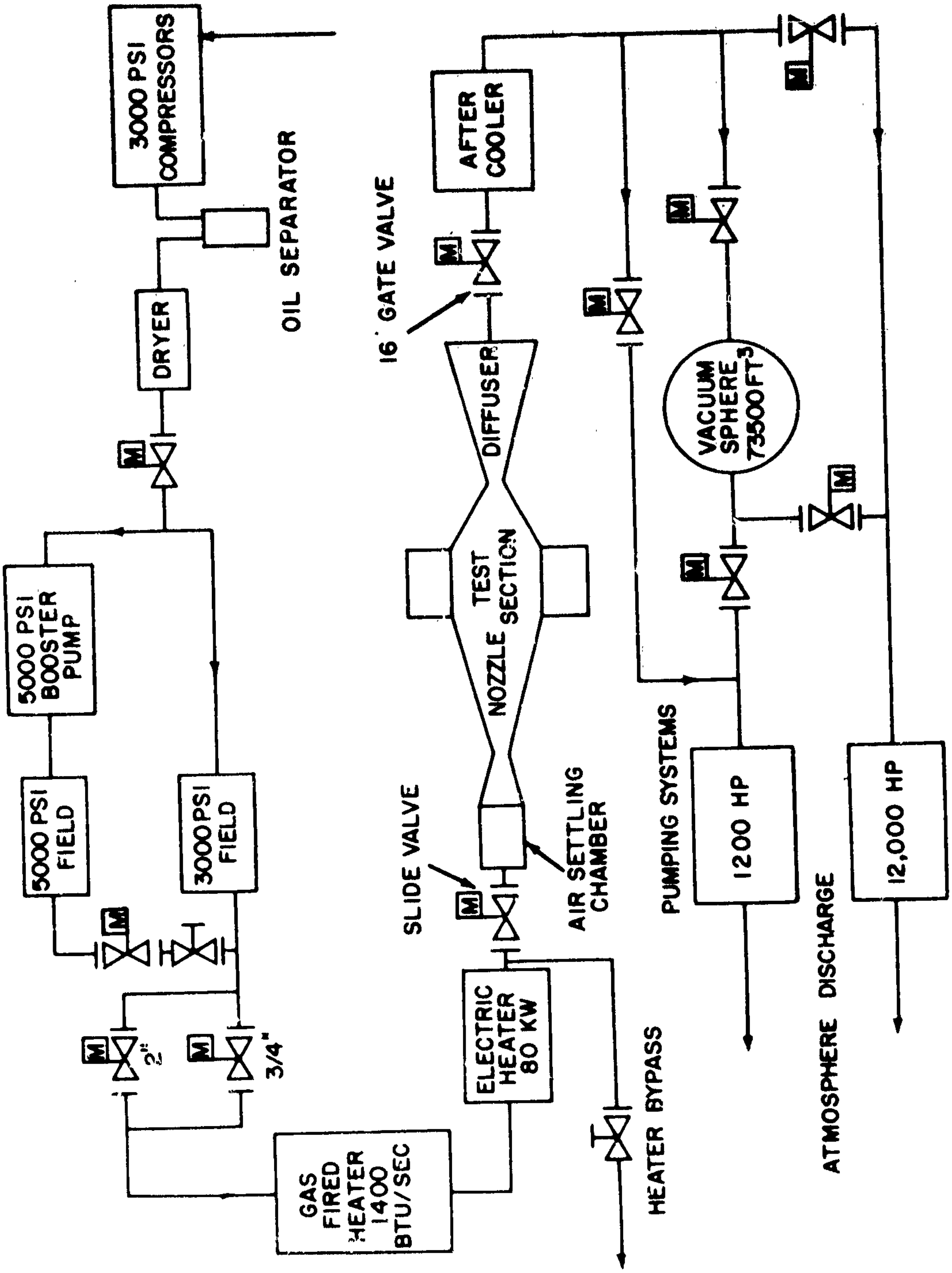


FIG. 3 SCHEMATIC DIAGRAM FOR NOL HYPERSONIC TUNNEL NO. 4

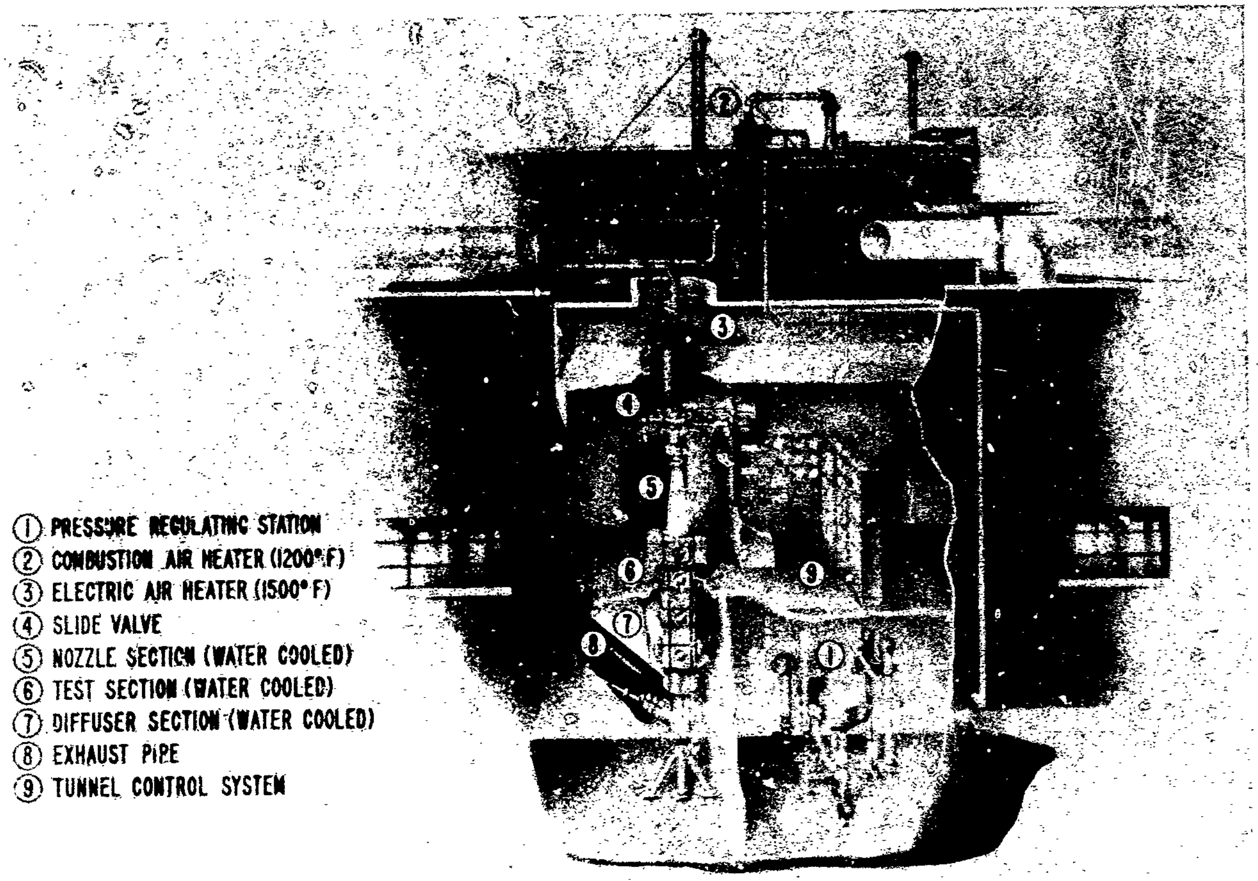


FIG. 4 ARTIST'S CONCEPTION OF NOL HYPERSONIC TUNNEL NO. 4

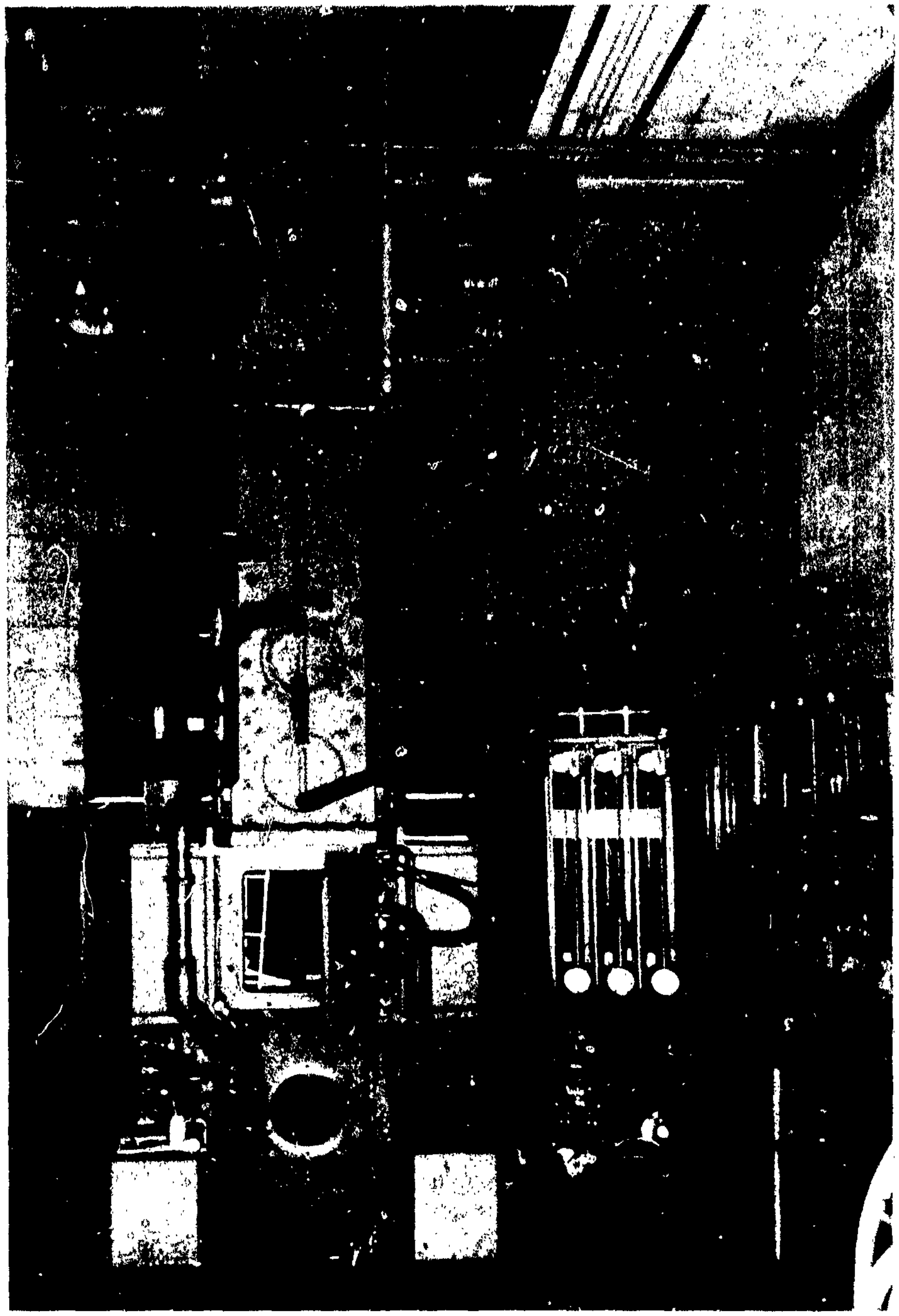


FIG. 5 TUNNEL WORKING SECTION

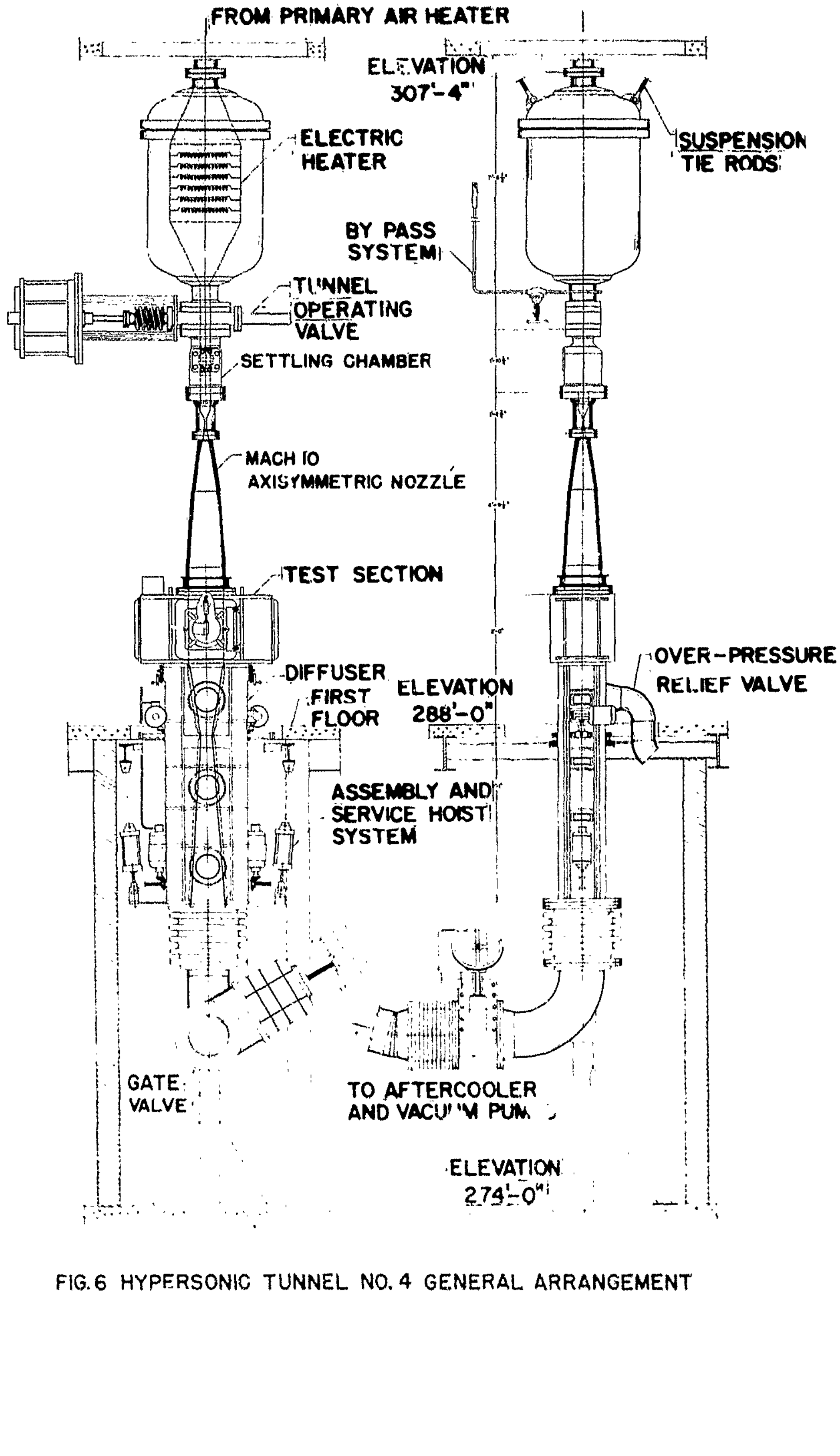


FIG. 6 HYPERSONIC TUNNEL NO. 4 GENERAL ARRANGEMENT

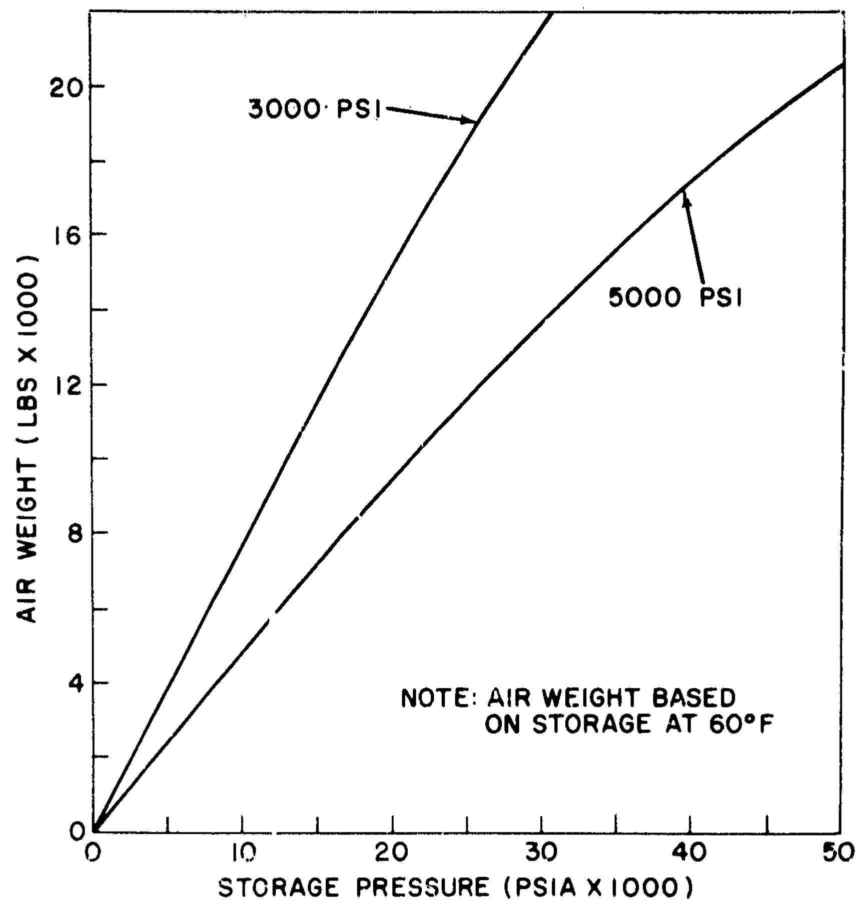


FIG. 7 AIR WEIGHT STORED IN HIGH-PRESSURE BOTTLES

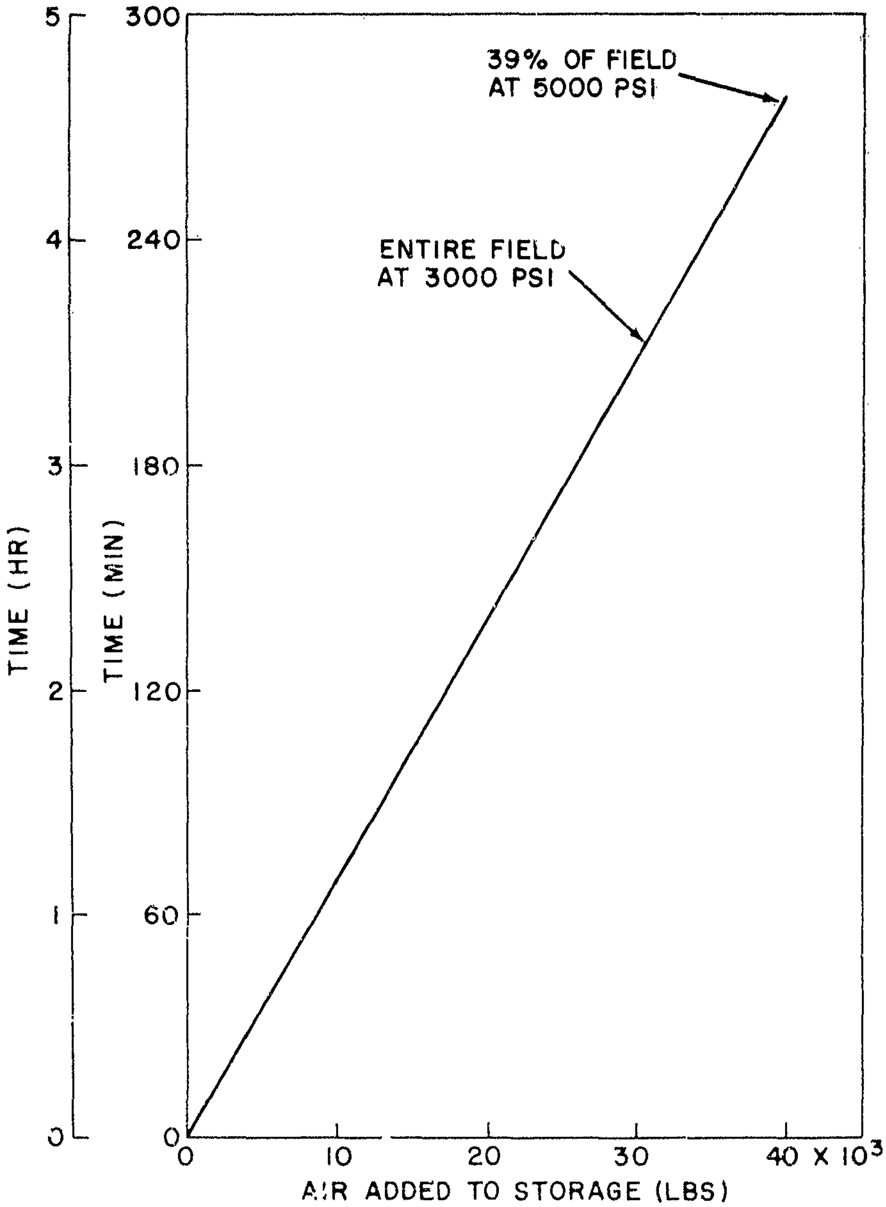


FIG. 8 TIME TO REPLENISH HIGH-PRESSURE AIR STORAGE SYSTEM

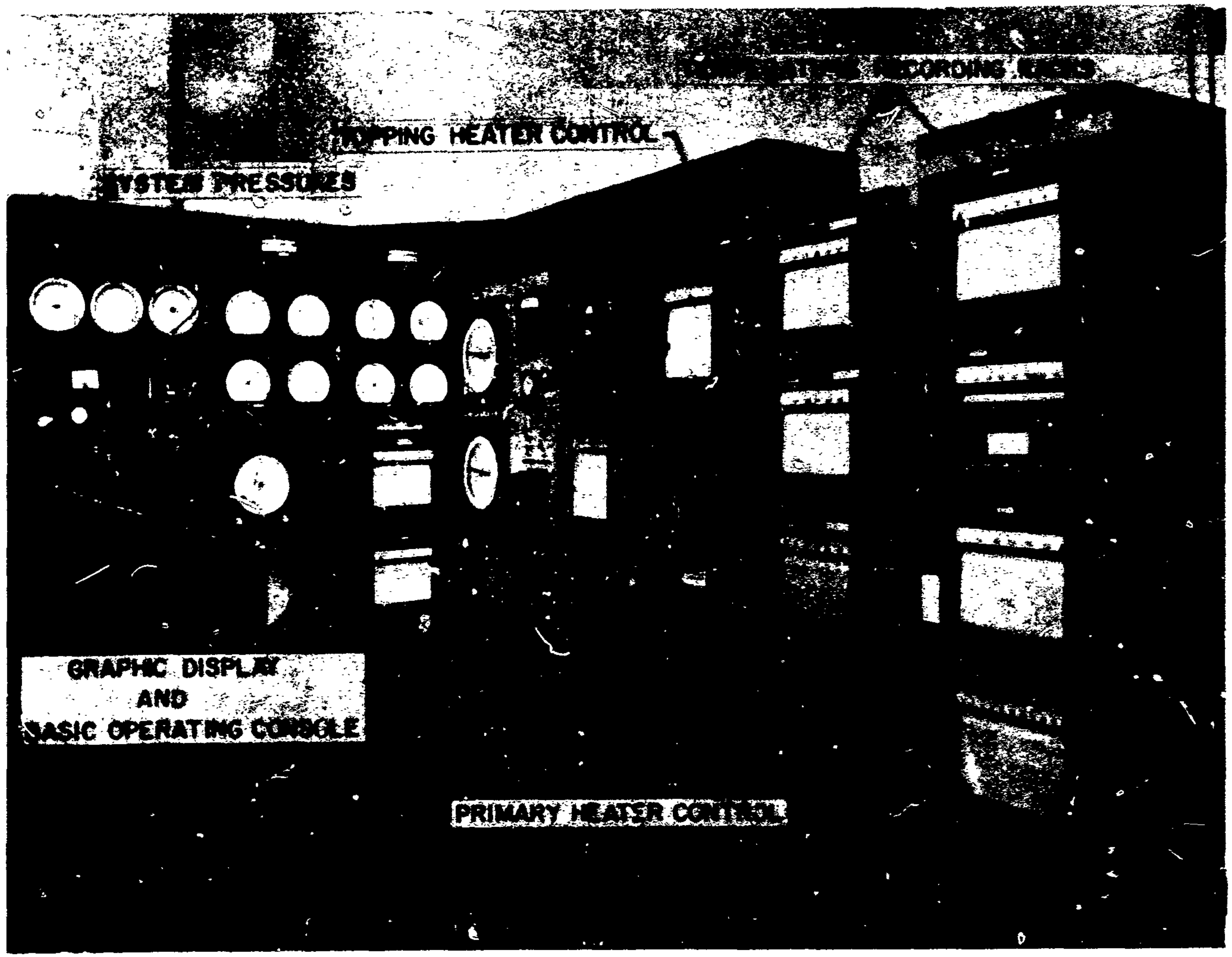


FIG. 9 TUNNEL CONTROL CENTER WITH OPERATING CONSOLE AND INSTRUMENTATION

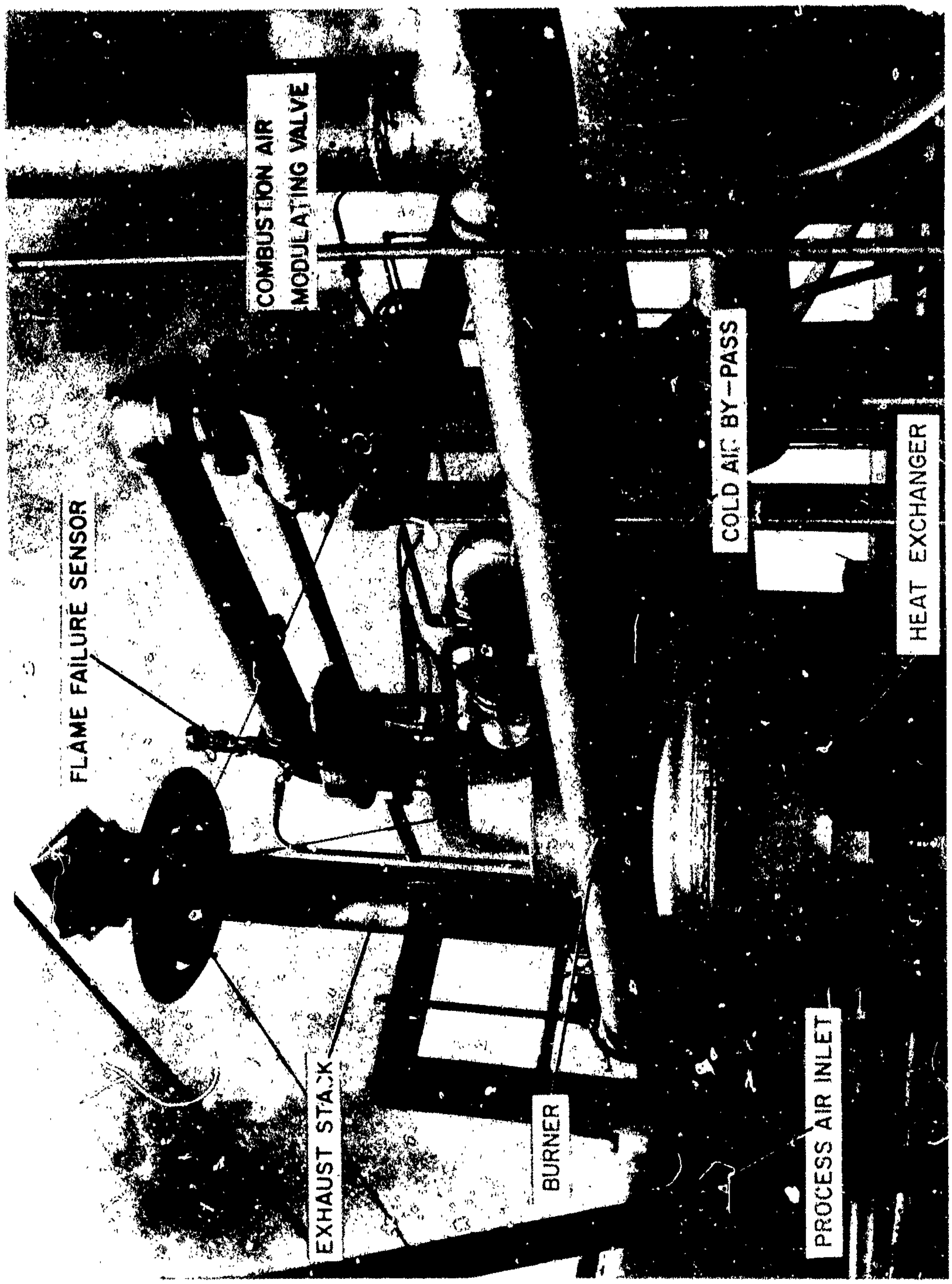


FIG. 10 PRIMARY AIR HEATER INSTALLATION

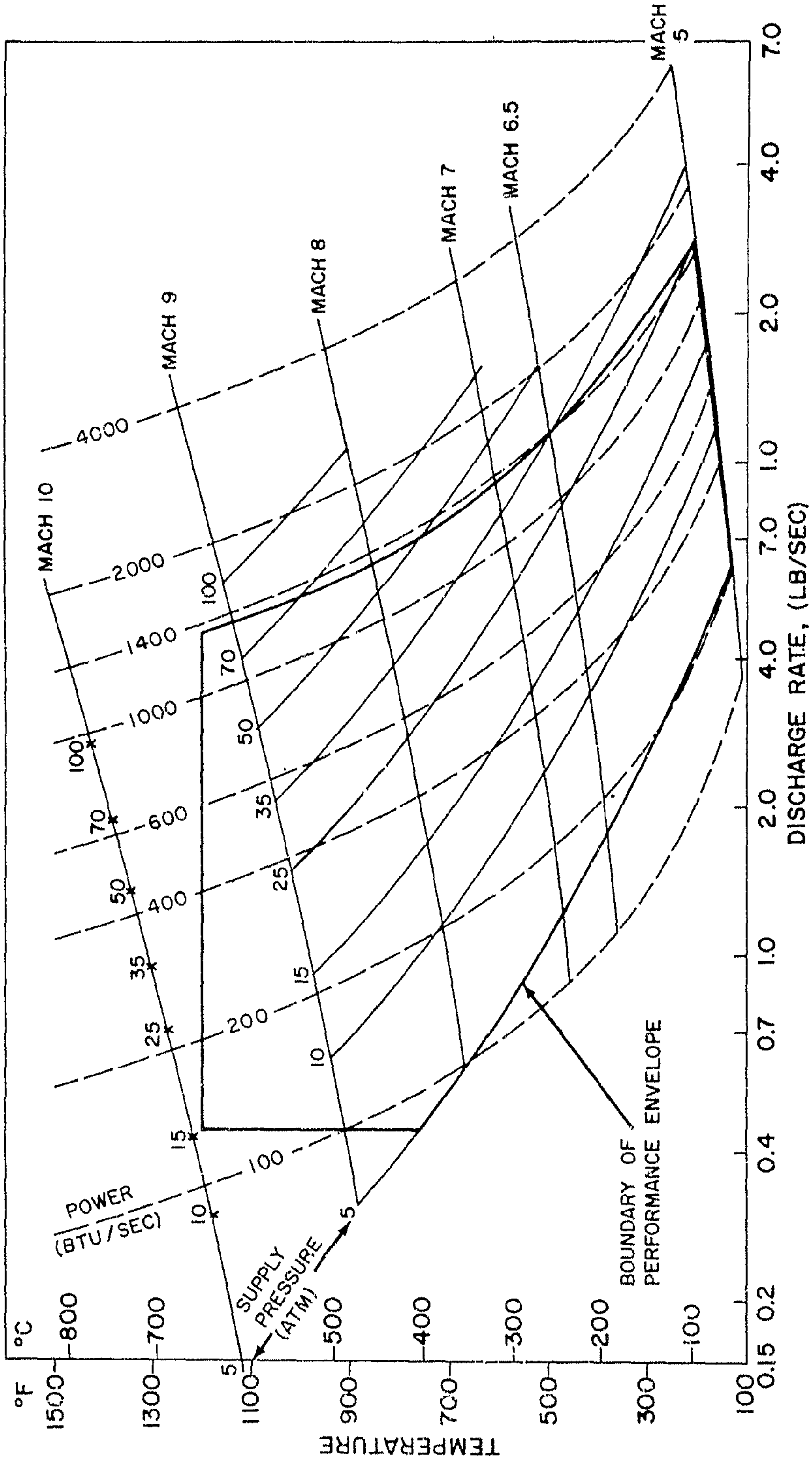
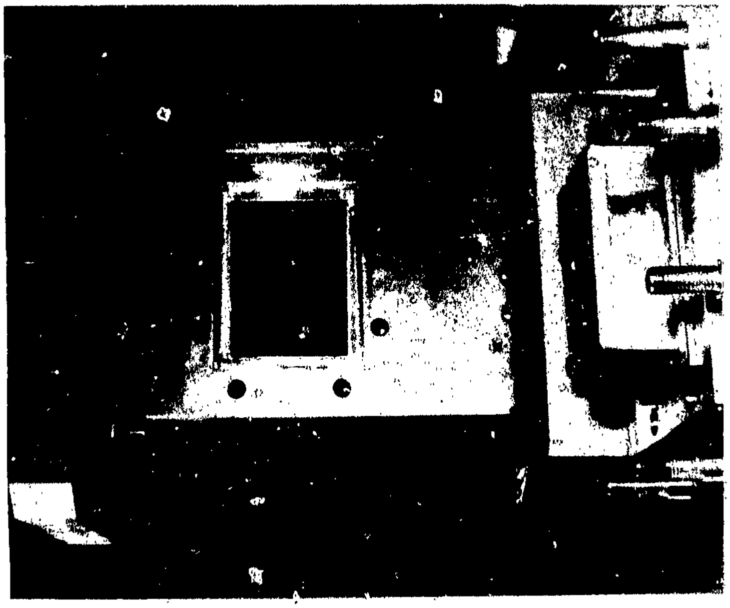


FIG. 11 NOL HYPERSONIC TUNNEL NO. 4 DESIGN OPERATION ENVELOPE



SIDE VIEW

BOTTOM VIEW

FIG. 12 AIR STAGNATION SECTION

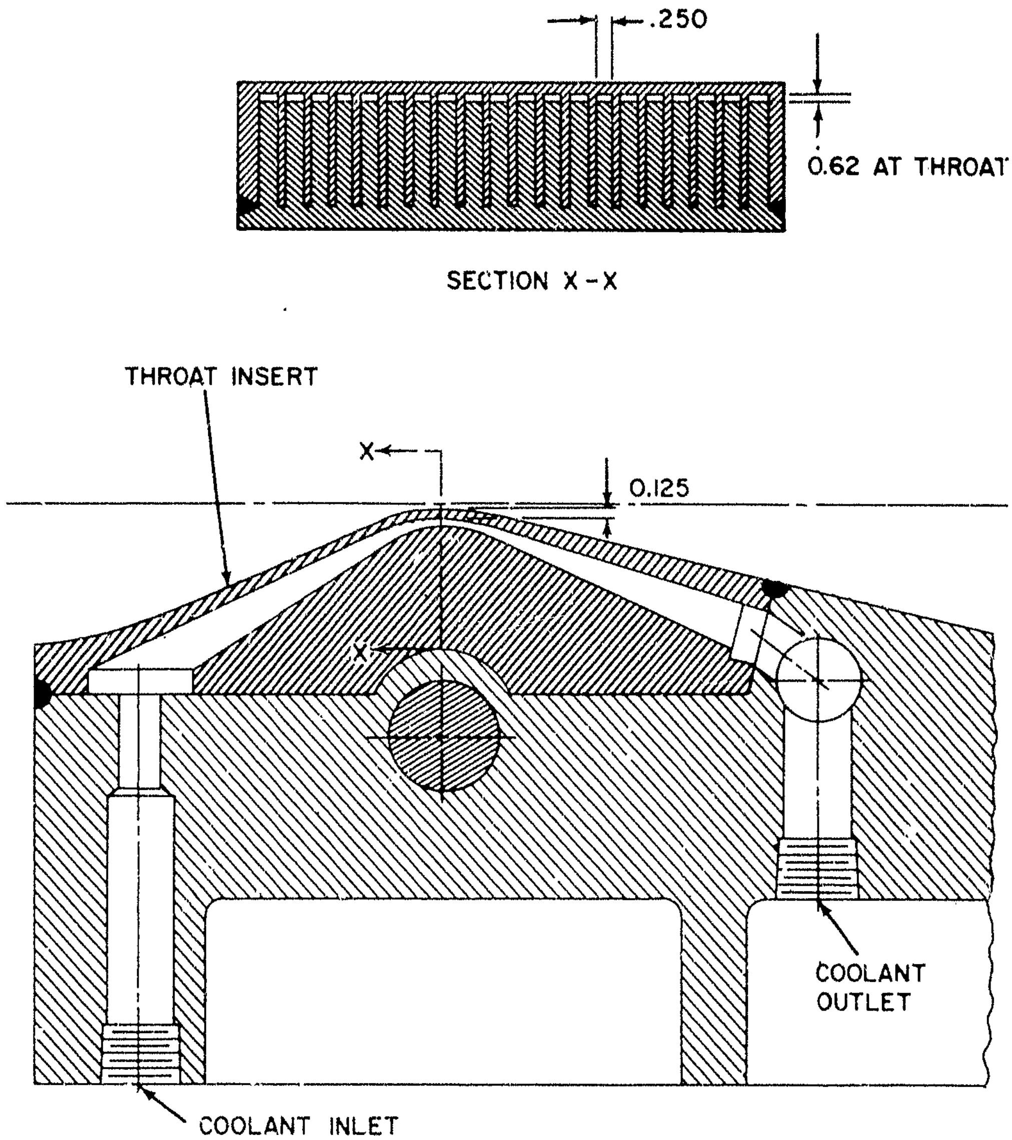


FIG. 13 TWO-DIMENSIONAL NOZZLE THROAT COOLING DESIGN

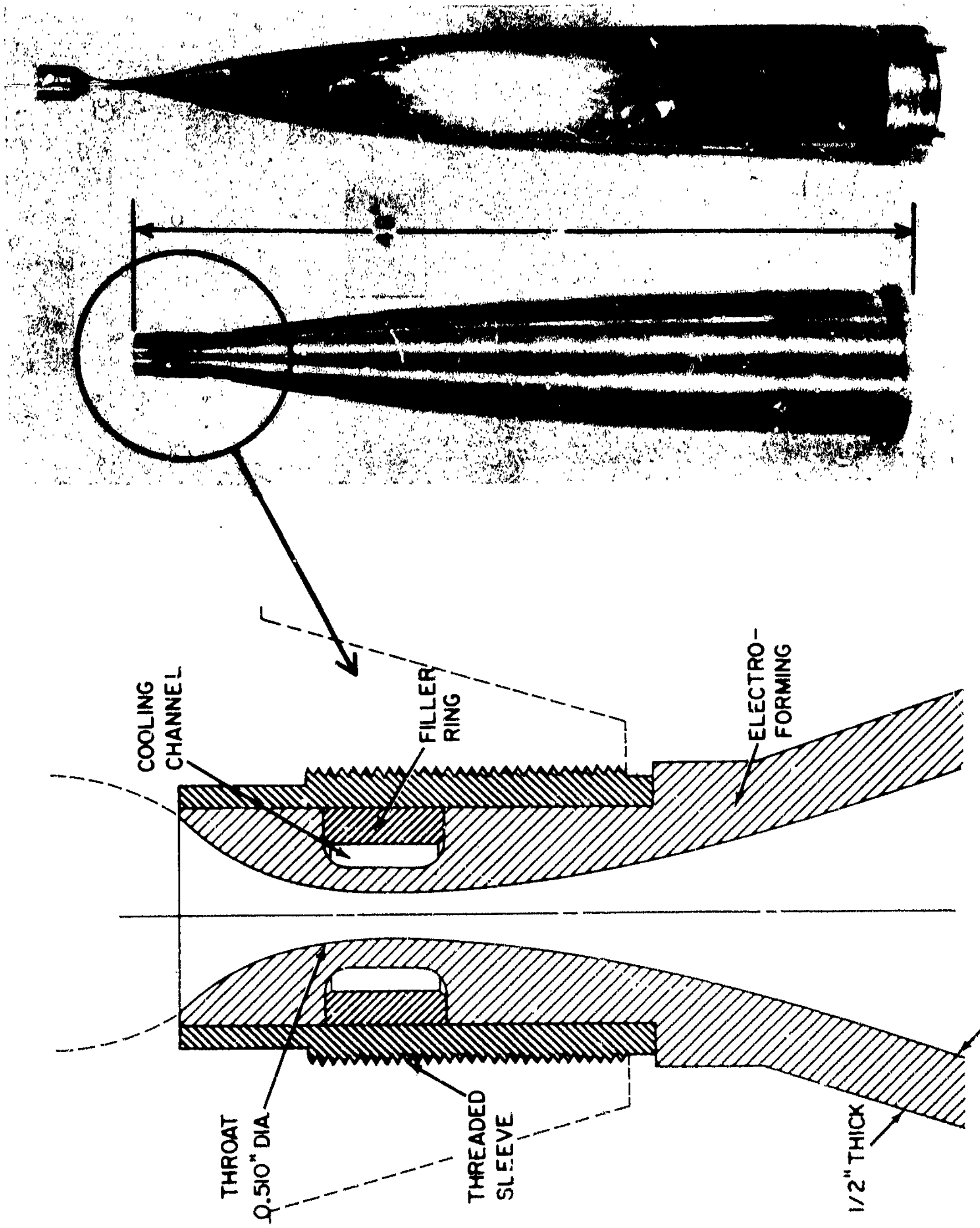


FIG. 14 MACH 8 AXIALLY SYMMETRIC NOZZLE

FIG. 15 TEST SECTION

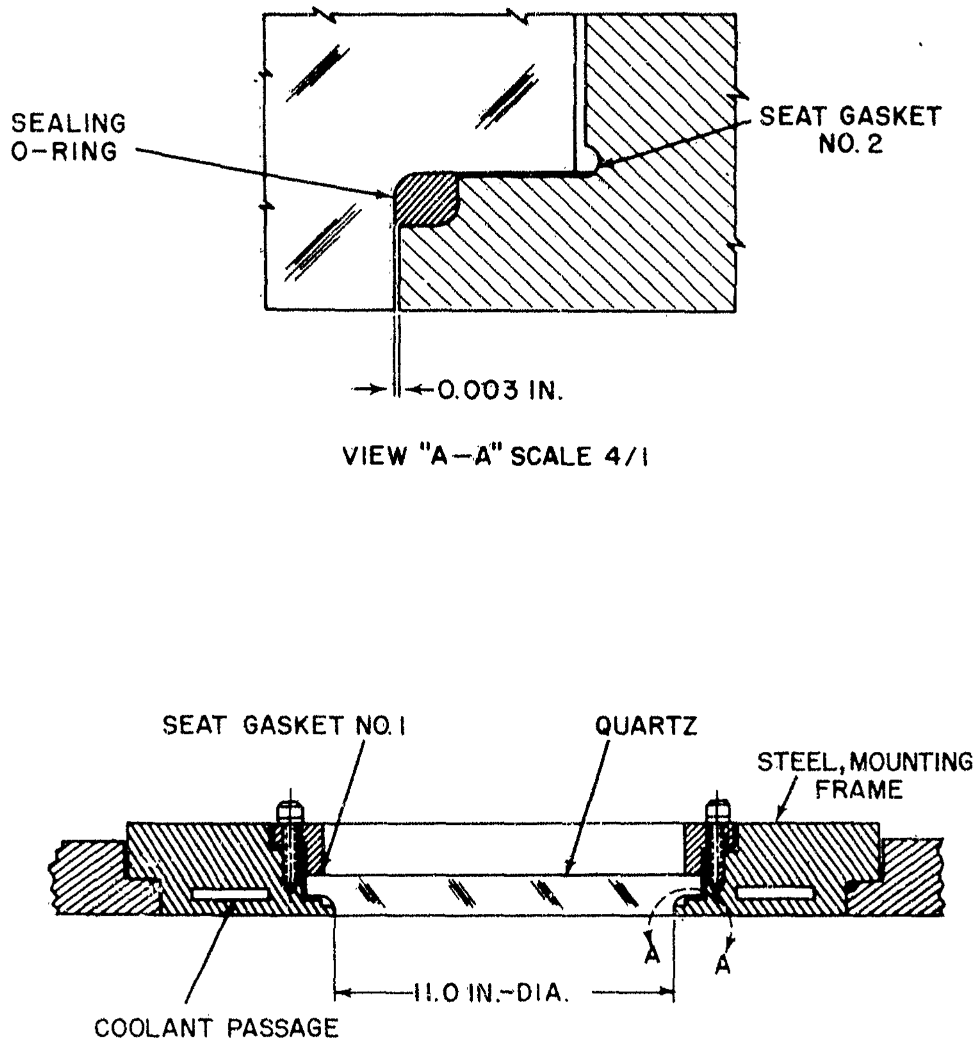


FIG. 16 OPTICAL WINDOW MOUNTING

FIG. 17 EXTERNAL VIEW OF DIFFUSER

FIG 18 INTERNAL VIEW OF DIFFUSER

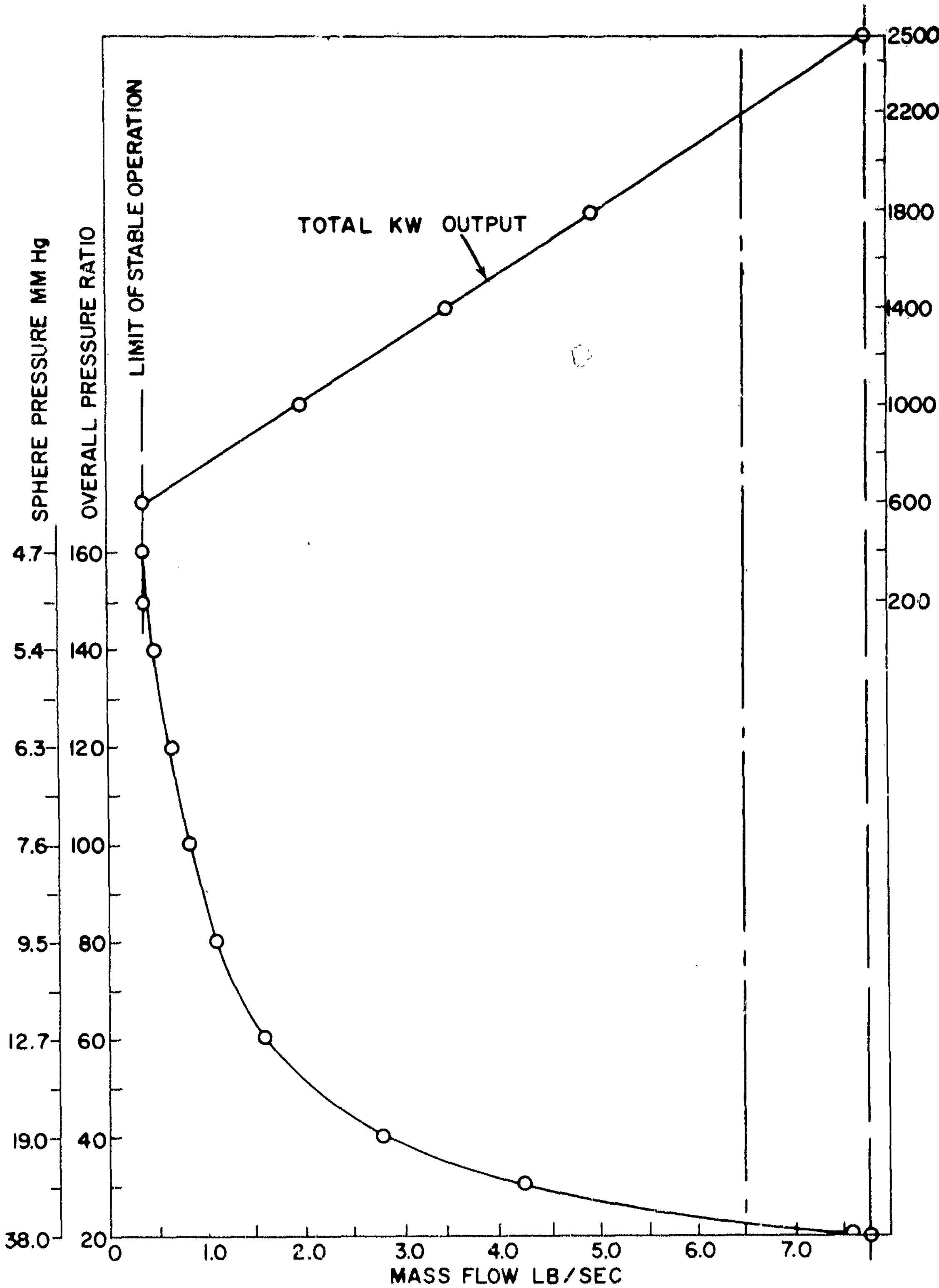


FIG. 19 PERFORMANCE OF CENTRIFUGAL COMPRESSORS IN SERIES OPERATION

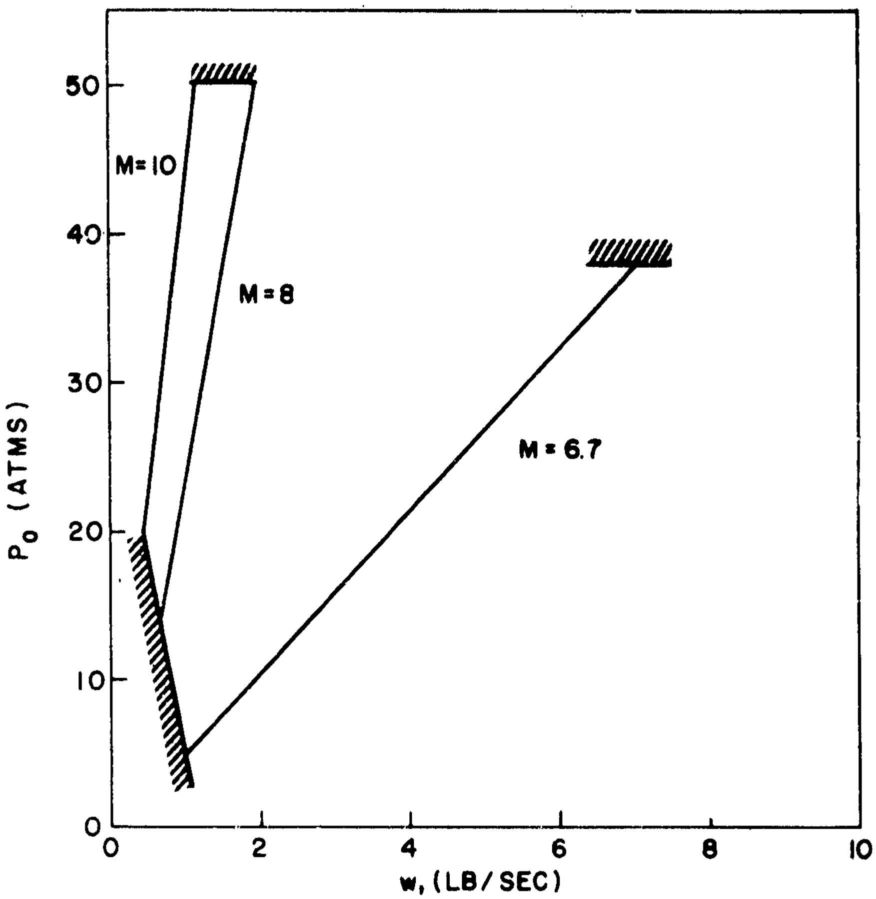


FIG. 20 DISCHARGE RATE FOR CONDENSATION THRESHOLD OPERATION

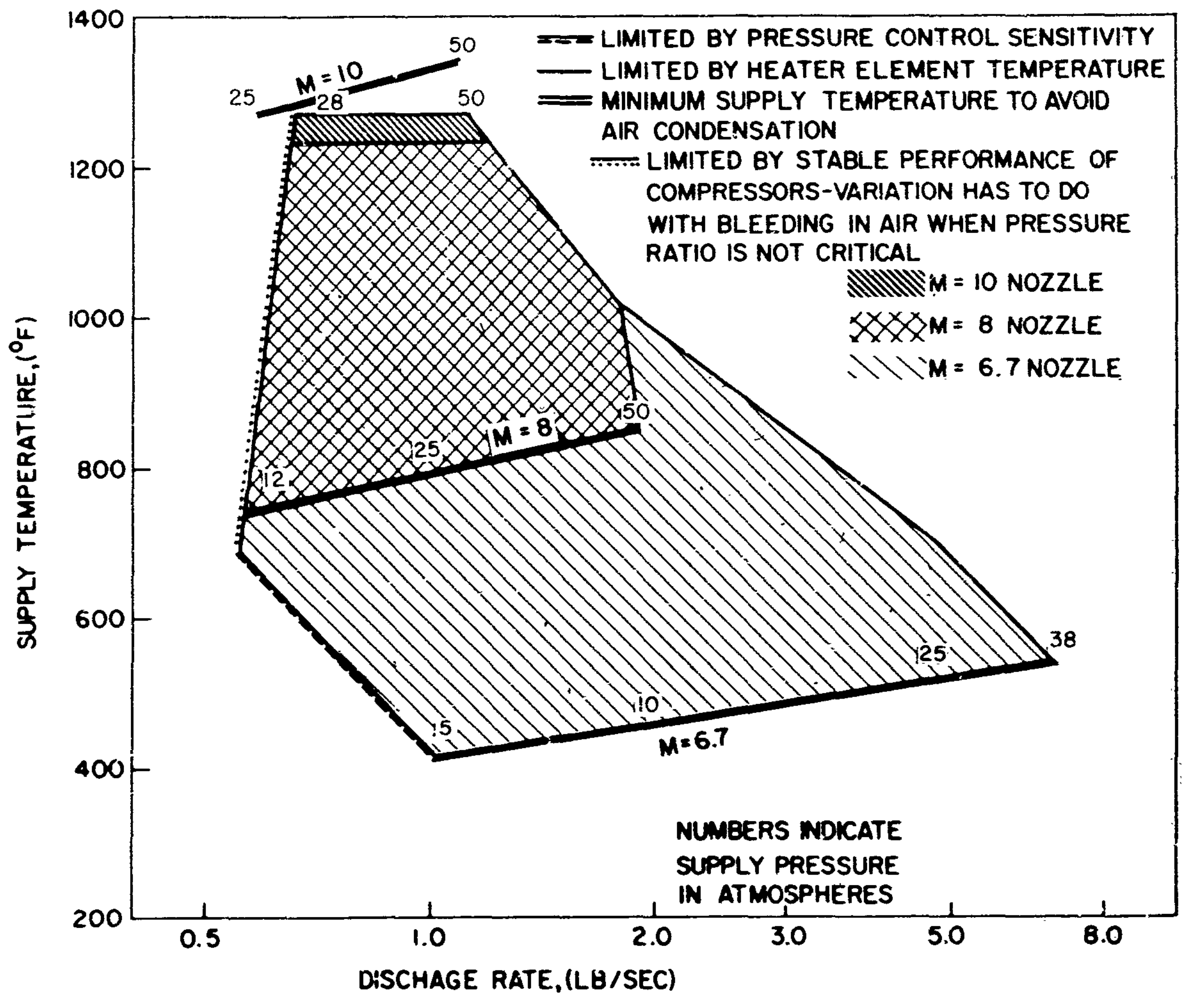
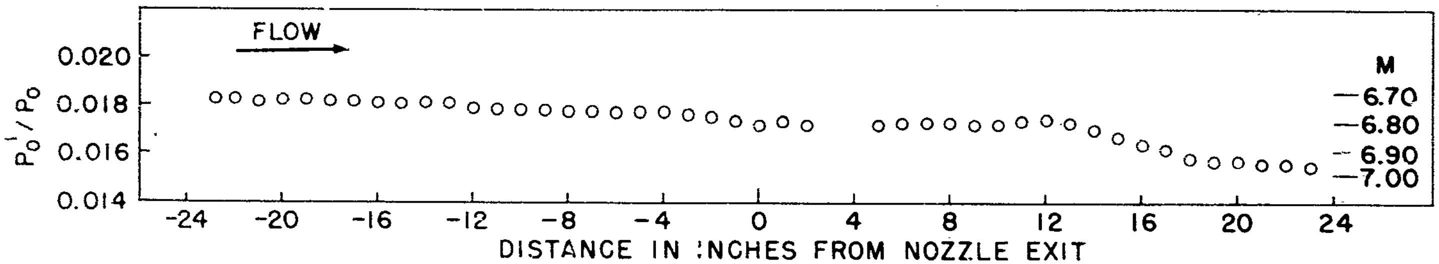
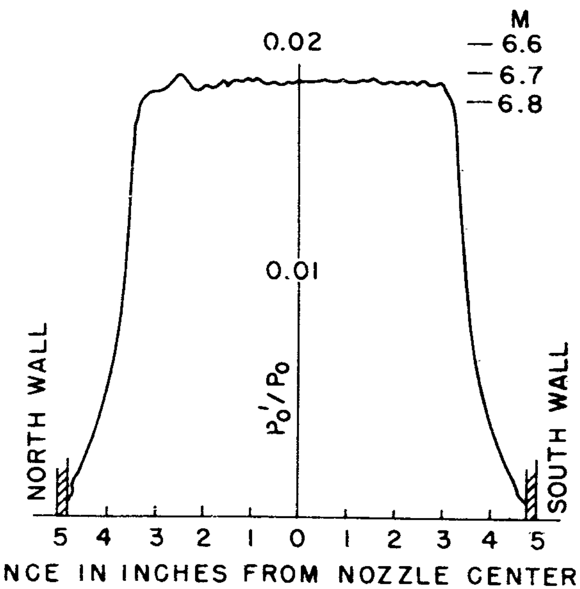


FIG. 21 NOL HYPERSONIC TUNNEL NO.4 PERFORMANCE ENVELOPE

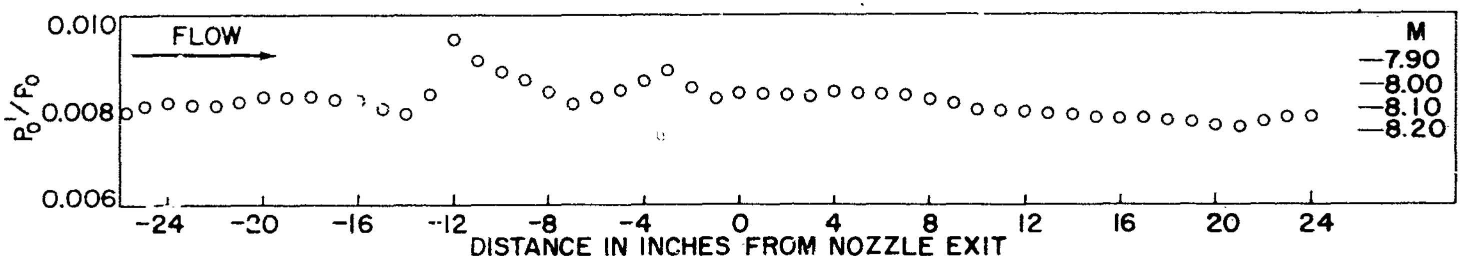


CENTERLINE PRESSURE DISTRIBUTION (P_0 = 500 PSIG T_0 = 310 °C)

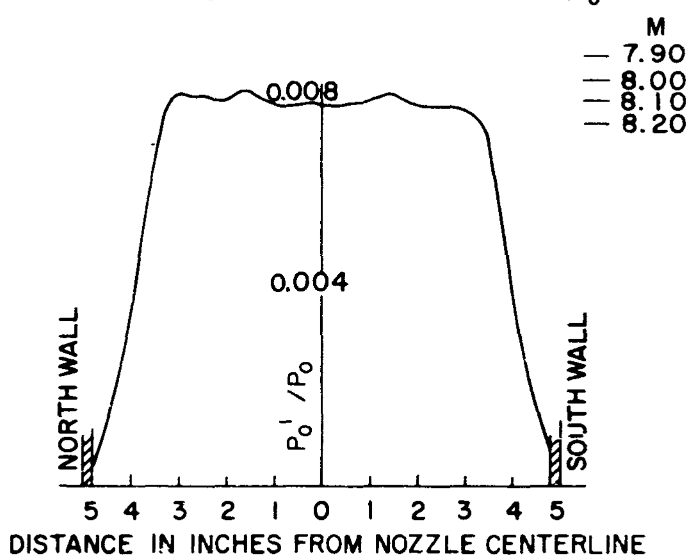


RATIO OF PITOT TO SUPPLY PRESSURE, 10" UPSTREAM OF NOZZLE EXIT (P_0=500 PSIG, T_0=300°C)

FIG. 22 CALIBRATION DATA FOR THE MACH NUMBER 6.7 TWO-DIMENSIONAL NOZZLE

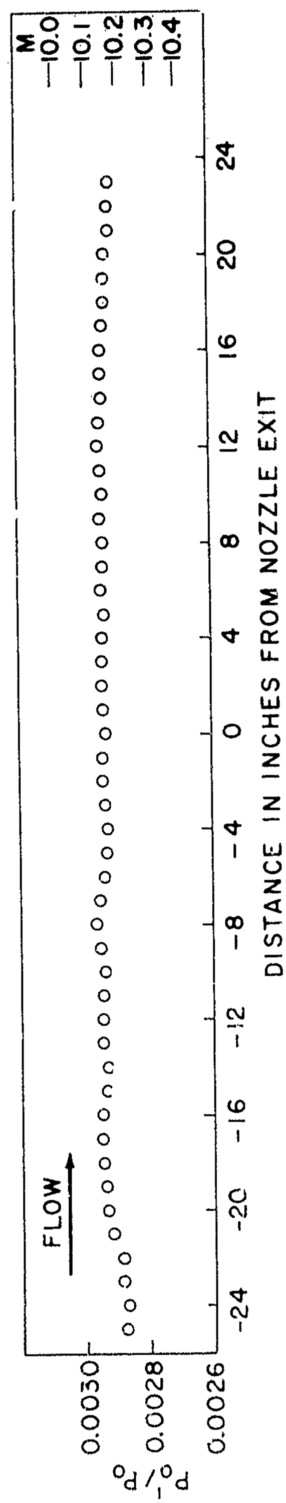


CENTERLINE DISTRIBUTION OF PITOT TO SUPPLY PRESSURE RATIO (P_0 = 500 PSIG T_0=448 °C)

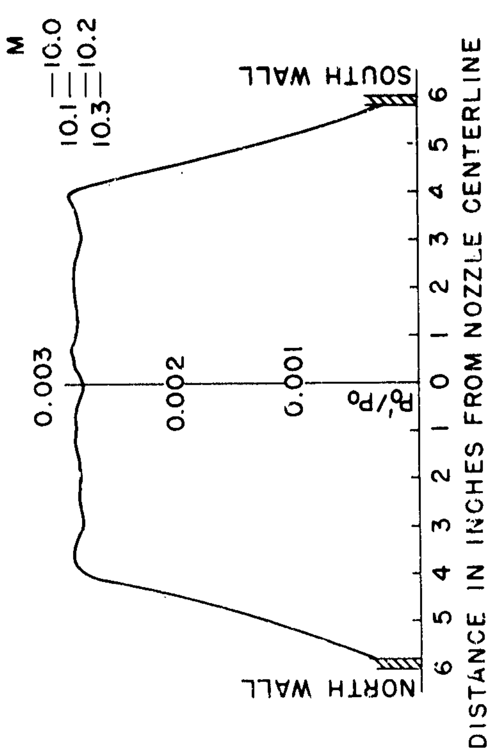


RATIO OF PITOT TO SUPPLY PRESSURE, 2" UPSTREAM OF NOZZLE EXIT (P_0=500 PSIG, T_0=449°C)

FIG. 23 CALIBRATION DATA FOR THE MACH NUMBER 8 AXISYMMETRIC NOZZLE



CENTERLINE DISTRIBUTION OF PITOT TO SUPPLY PRESSURE RATIO
(P_o = 735 PSIG T_o = 654 °C)



RATIO OF PITOT TO SUPPLY PRESSURE, 5" UPSTREAM OF NOZZLE EXIT (P_o = 735 PSIG, T_o = 645°C)

FIG.24 CALIBRATION DATA FOR THE MACH NUMBER 10 AXISYMMETRIC NOZZLE

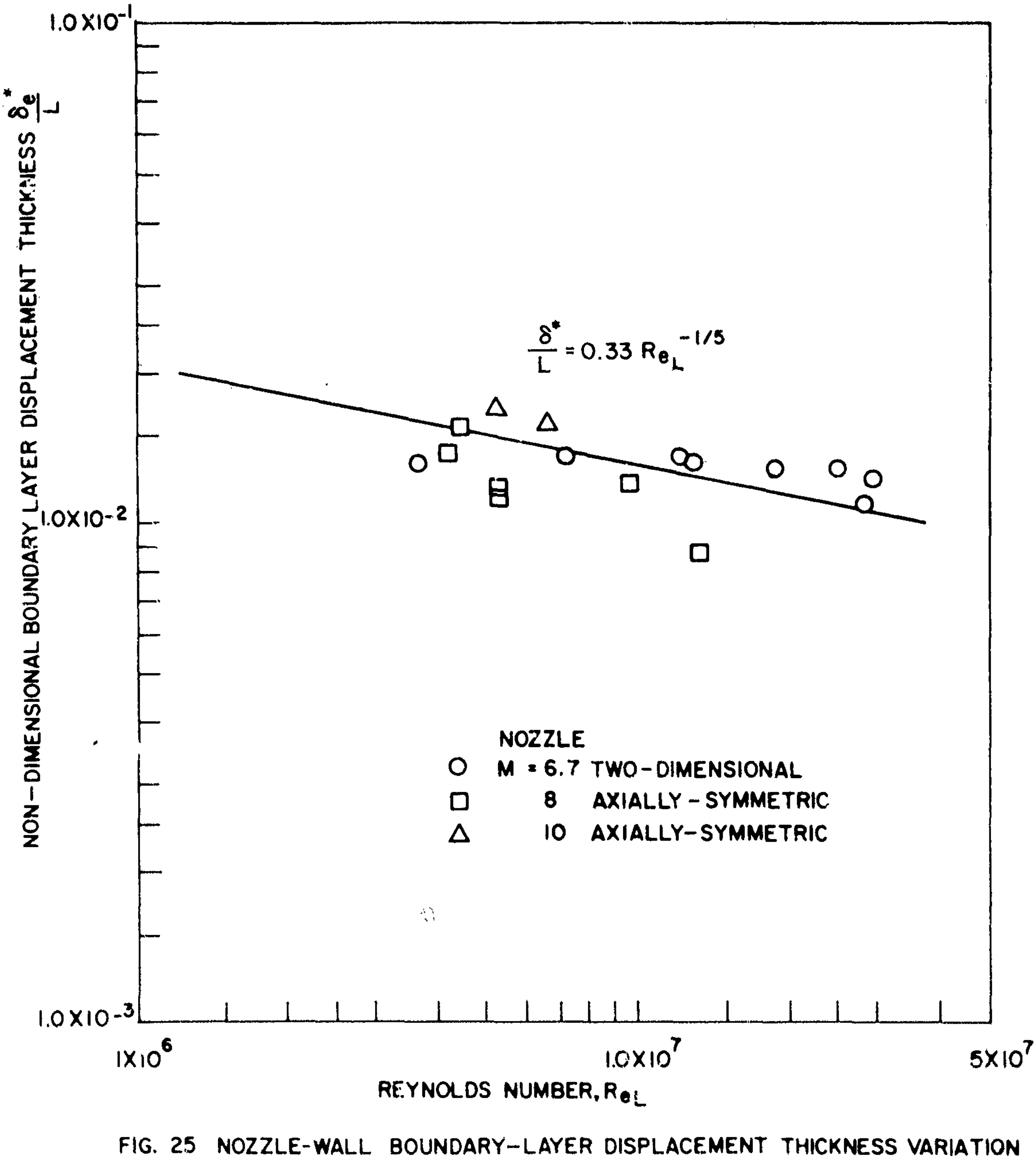


FIG. 25 NOZZLE-WALL BOUNDARY-LAYER DISPLACEMENT THICKNESS VARIATION

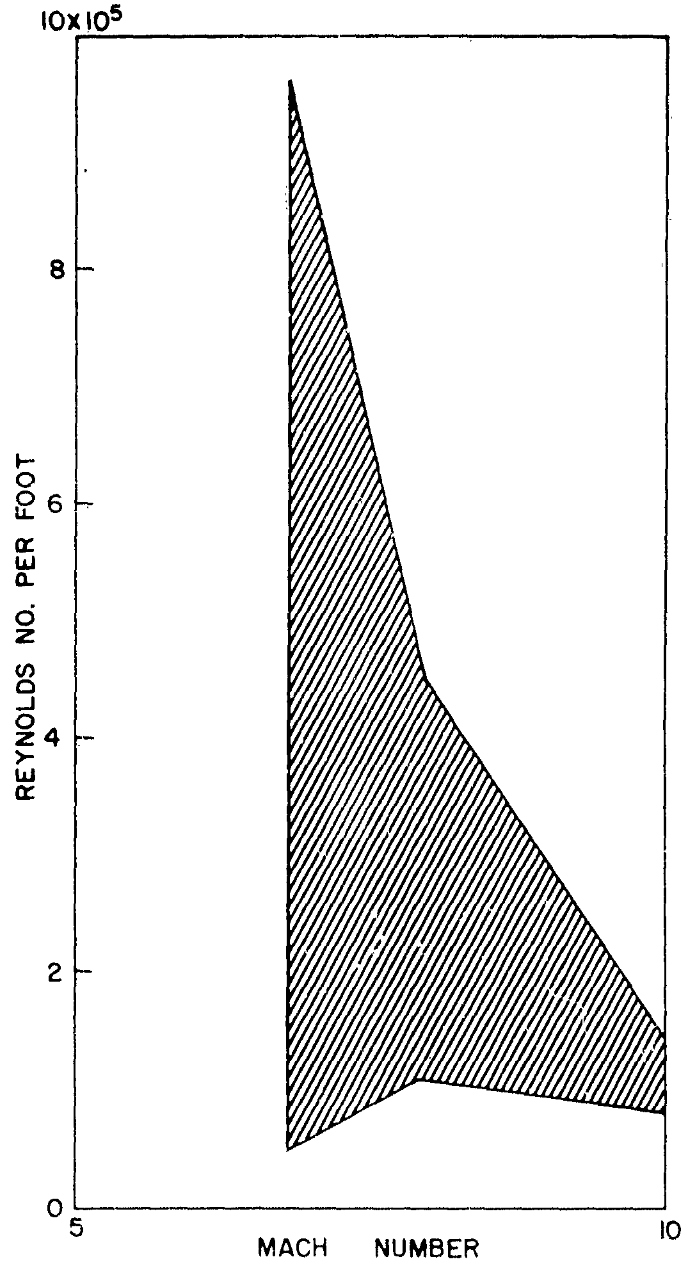


FIG. 26 REYNOLDS NUMBER CAPABILITY

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